Probing the Equation of State of Dense Matter with a Merged XEUS/Con-X Mission

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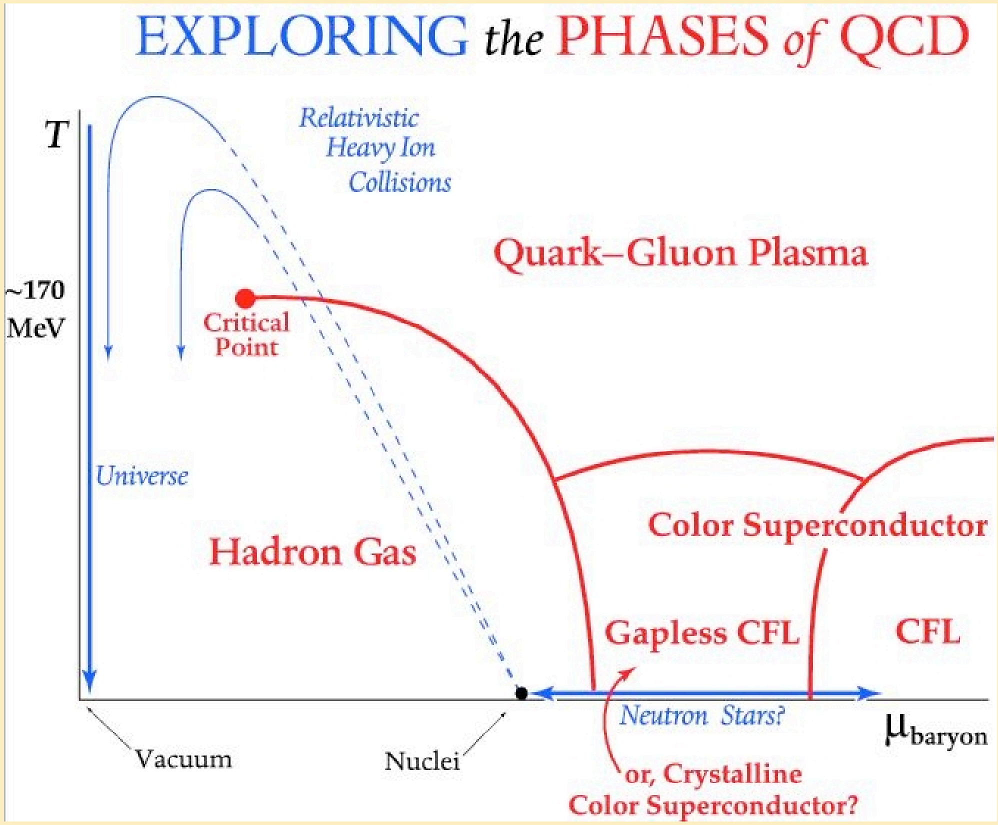
Thanks to the following people for assistance:
Lars Bildsten *(UCSB)*
Jean Cottam *(NASA/GSFC)*
Mariano Méndez *(SRON)*
Frits Paerels *(Columbia)*
Dimitrios Psaltis *(Arizona)*
Krishna Rajagopal *(MIT)*
Robert Rutledge *(McGill)*
Tod Strohmayer *(NASA/GSFC)*

This presentation includes some slides taken directly from Mariano Mendez's talk, since he was unable to attend this meeting.

Fundamental question:
What happens to matter when it is squeezed?

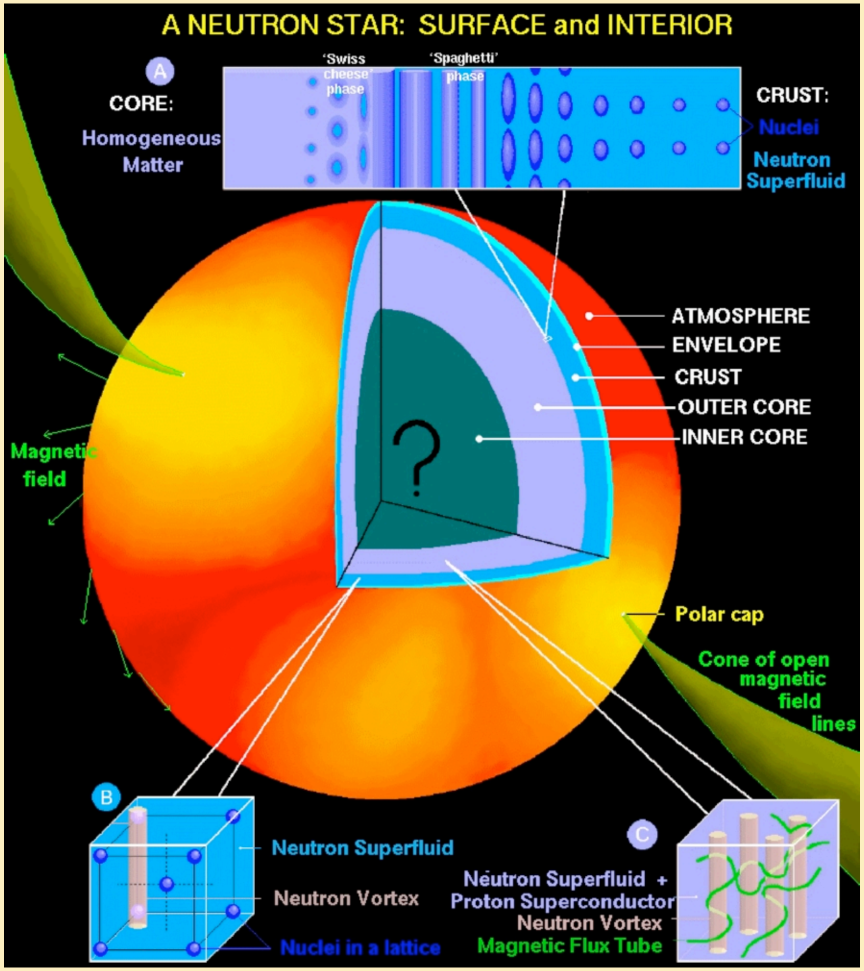
At its most extreme case, this question leads to collapse into black holes.. In the regime leading up to that point, it explores the physics of quantum chromodynamics (QCD), the theory of strong interactions.

The "Condensed Matter Physics" of QCD



Krishna Rajagopal (2004)

- The early universe explored the high temperature regime
- Relativistic heavy ion collision experiments are exploring transition to quark-gluon plasma
- The high density "low" temperature regime is inaccessible to laboratory experiment. The only way to study this regime is through the astrophysics of neutron stars.



Credit: Dany Page, in Lattimer & Prakash (2004)

Neutron star equation of state is known for the outer parts of the star, but is unconstrained for the high-density inner core.

This uncertainty arises from an inability to extrapolate our knowledge of normal nuclei (with 50% proton fraction) to the high-density regime of nearly 0% proton fraction.

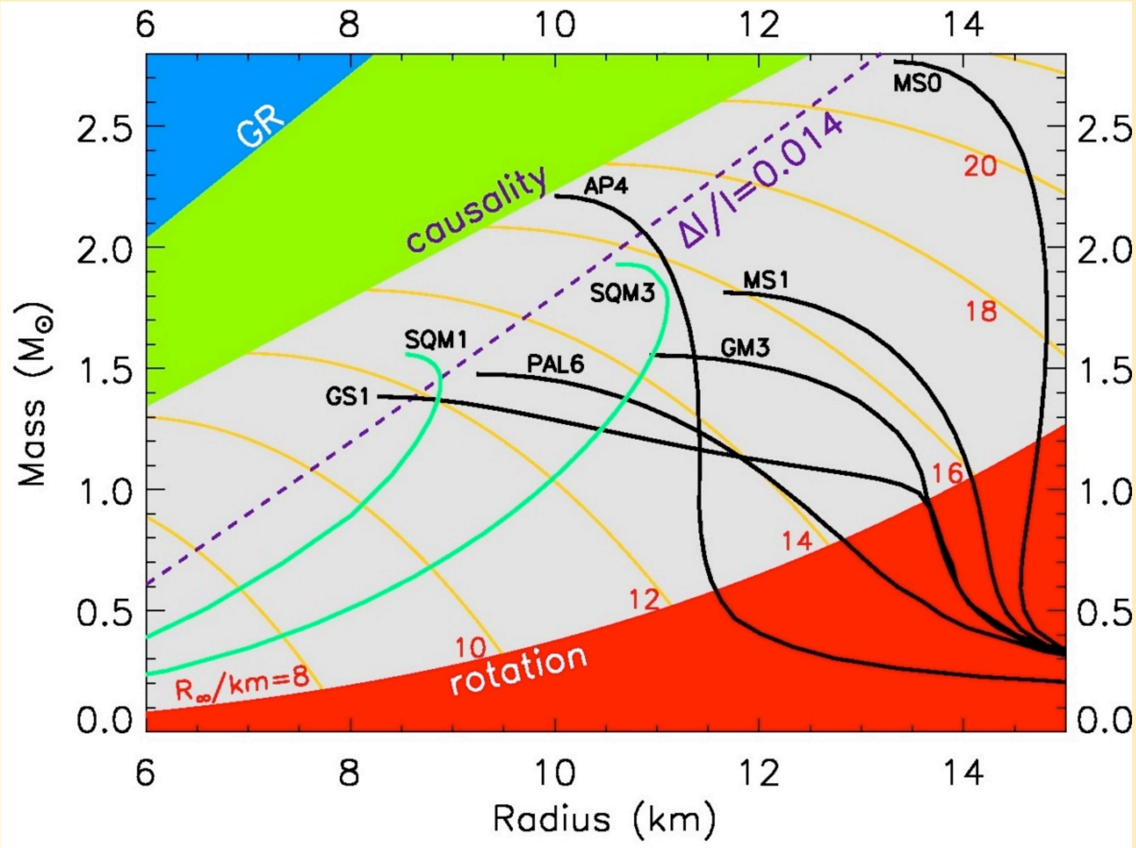
Consequently, equation of state models depend upon assumptions about the matter phase of the inner core:

- hadronic matter
- Bose-Einstein condensates (pion, kaon)
- Quark matter

Each new phase of matter increases the compressibility of the star.

Measurements of the NS mass and radius are the only way to constrain the models.

Neutron Star Mass-Radius Relation



Lattimer & Prakash (2004)

Some regions of the M-R diagram are excluded by physical grounds:

- GR ($R > R_{\mathrm{Schwarzschild}}$)
- Causality ($v_{\mathrm{sound}} < c$)
- Rotation (existence of 641 Hz psr)

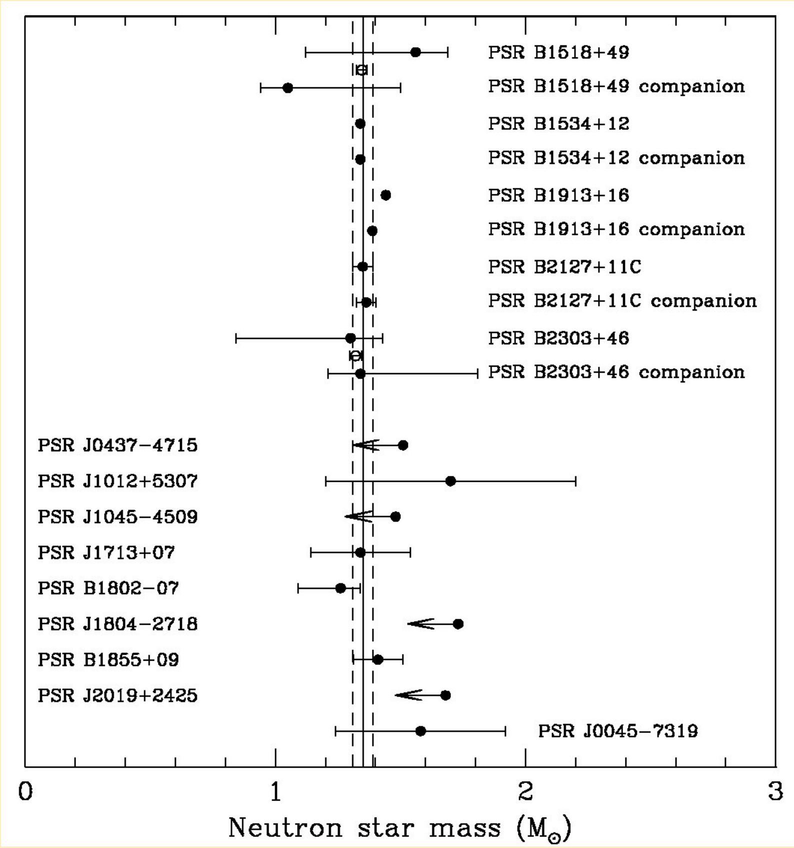
Quark matter EOS (green) have very different form than "normal" NS, since quark stars are bound by strong force rather than gravity.

Radiation radius R_∞, shown by orange curves, depends on R and M.

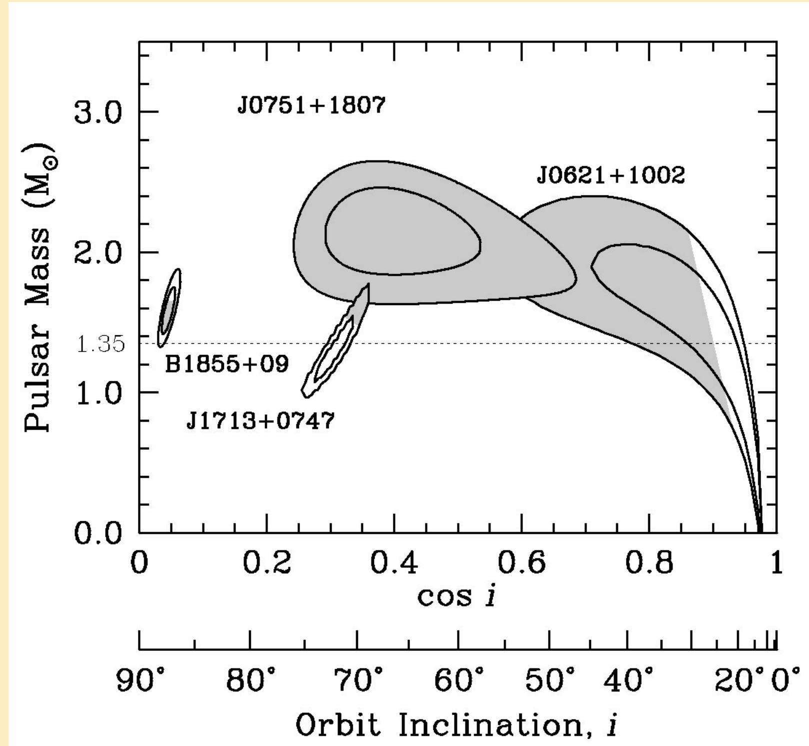
We want to map out the actual M-R curve for neutron stars. We know that neutron stars likely to have a range of masses owing to mass accretion in binaries....

X-ray observations offer essentially the only way to go after radius measurements.

Neutron Star Mass Measurements



Thorsett & Chakrabarty (1999)



Nice et al. (2004)

- Precise dynamical measurements of radio pulsar binaries, $\langle M \rangle = 1.35\ M_{sun}$
- Growing evidence for massive (~2 M_{sun}) pulsars, presumably from sustained mass transfer
- Measurements of radius more difficult...

Neutron Star Radius Measurements and Constraints

- Spectroscopy:
  - ♣ Solid angle measurements (R_∞^2/d^2) from flux and effective temperature
  - ♣ Cooling curves (constrain internal structure)
  - ♣ Redshifted photospheric lines (M/R, potentially M/R^2 and/or $\Omega R \sin I$)

- Timing:
  - ♣ Kilohertz quasi-periodic oscillations
  - ♣ X-ray burst oscillations (amplitude, harmonic content, pulse phase spectroscopy)
  - ♣ Accretion-powered pulsars

Spectroscopy: Solid Angle Measurements

Classical astronomy: Use continuum spectrum to measure flux and effective temperature, hence determine solid angle of emission source,

$$\left(\frac{R_\infty}{d}\right)^2 = \frac{F_\infty}{\sigma T_{\mathrm{eff},\infty}^4}$$

For known source distance, this yields radius. Note that for compact stars (M/R very large), flux is subject to significant gravitational redshift along path to observer at infinity, with redshift $z(M/R)$ given by

$$1 + z = \left(1 - 2GM/Rc^2\right)^{-1/2}$$

Observer at infinity thus measures different values of T, F, R:

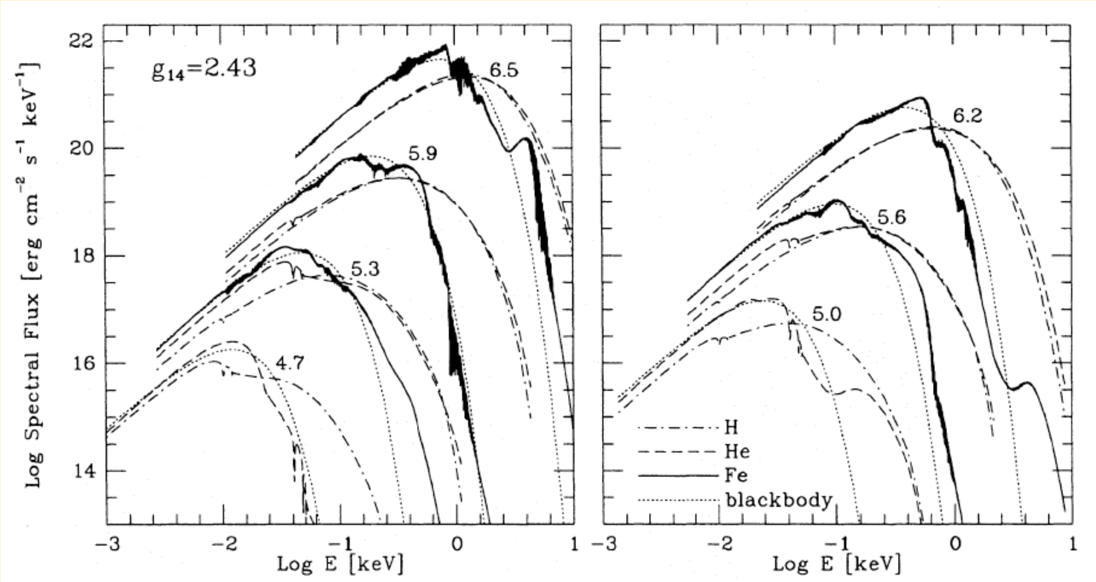
$$T_{\mathrm{eff},\infty} = \frac{T_{\mathrm{eff}}}{1+z} \qquad F_\infty = \frac{F}{(1+z)^2} \qquad R_\infty = R\,(1+z)$$

("radiation radius")

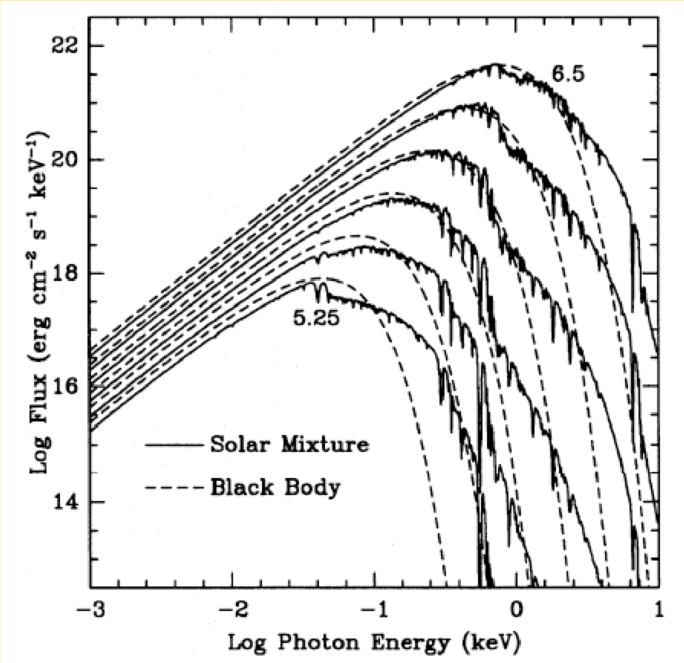
Solid Angle Measurements: Complications

• Blackbody emission distorted by thin neutron star atmosphere. Presence of any heavy elements will imprint characteristic energies on spectrum. Strong NS surface gravity will stratify material in seconds, with lightest elements rising to the surface.

<u>Non-magnetic neutron star atmosphere spectra</u>



Zavlin et al. (1996)



Rajagopal & Romani (1996)

Solid Angle Measurements: Complications (2)

- Strong neutron star magnetic fields complicate atmosphere models.

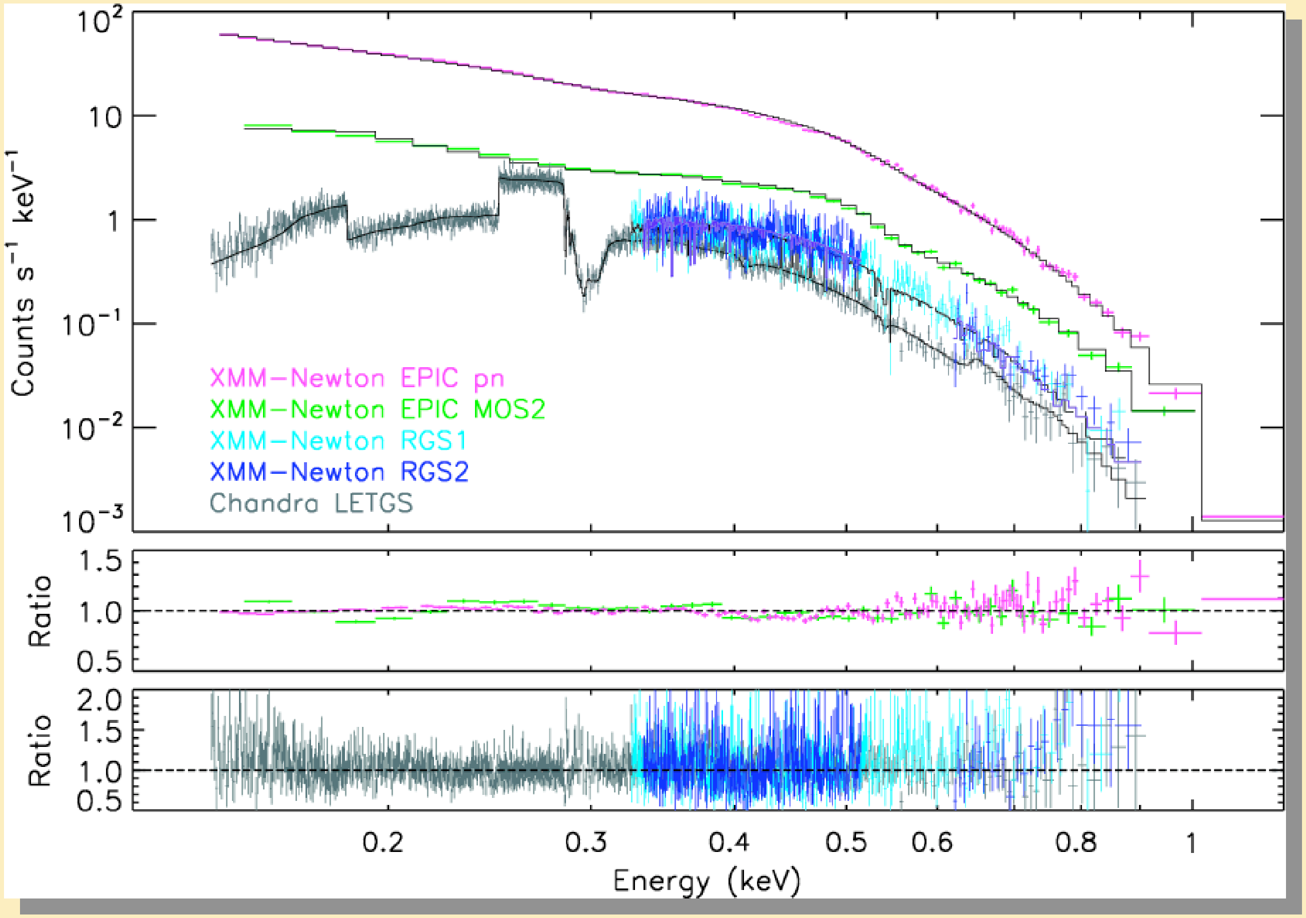
- Magnetospheric activity in young neutron stars can generate strong non-thermal emission that outshines the thermal emission.

- Pulsar activity in old neutron stars can lead to highly anisotropic temperature distribution, with poles hotter than rest of star.

- In X-ray binaries, accretion disk emission generally brighter than thermal emission from neutron star surface (except in quiescent soft X-ray transients...)

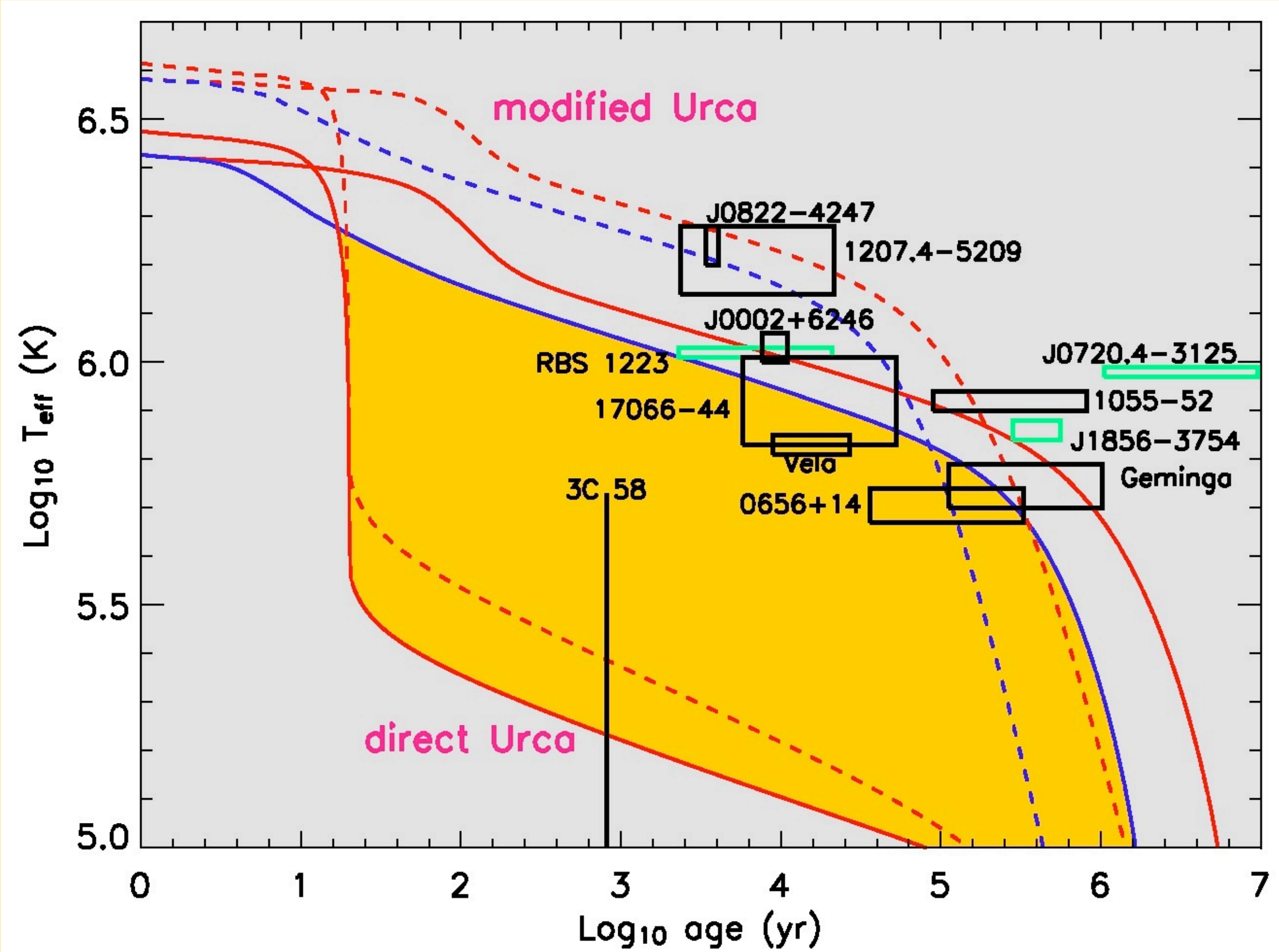
- Distance measurements usually of limited precision. Exceptions: globular cluster sources, parallax (eventually with *SIM*), radius expansion bursts?

Isolated Neutron Star RX J1856.5-3754



Burwitz et al. (2003)

- No line features detected with Chandra and XMM



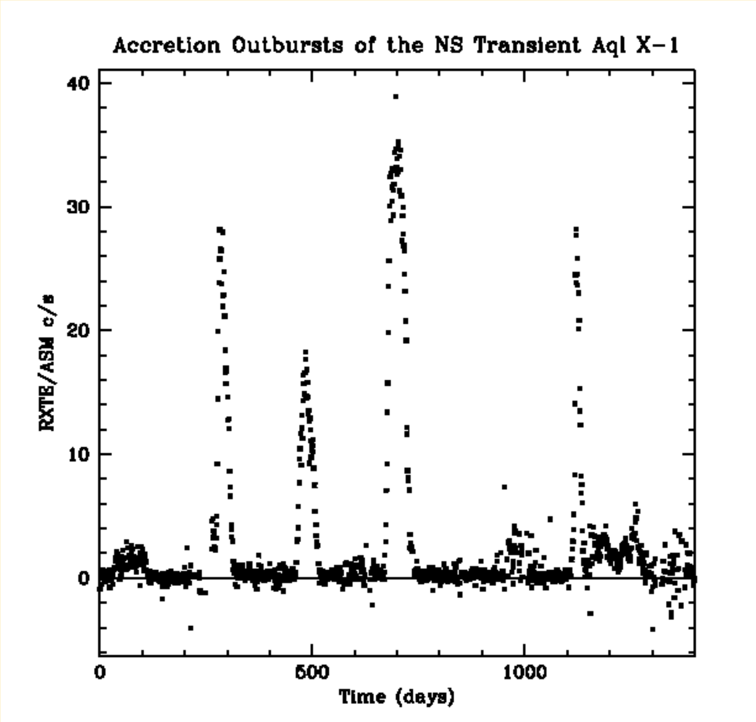
Lattimer & Prakash (2004)

Neutron star cooling curves constrain internal structure, since neutrino cooling rates are extremely dependent on nature of matter (phases) in the stellar core.

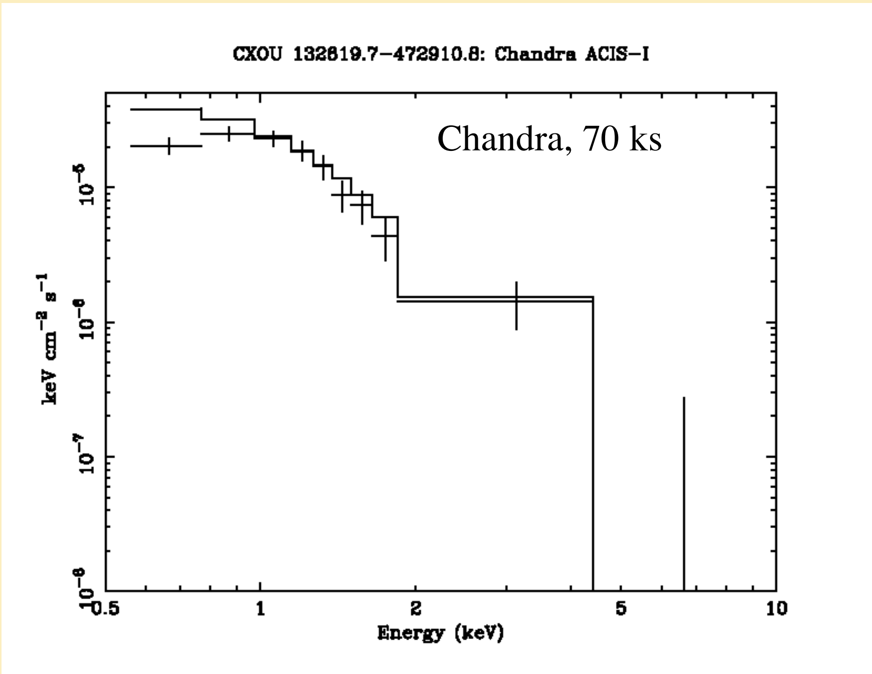
Soft X-Ray Transients in Quiescence

• Low magnetic field strengths ($B<10^{10}$ G). Thermal emission dominates in quiescence, generated by heating of core by accretion via crustal heating (e.g., Brown, Bildsten, & Rutledge 1998).

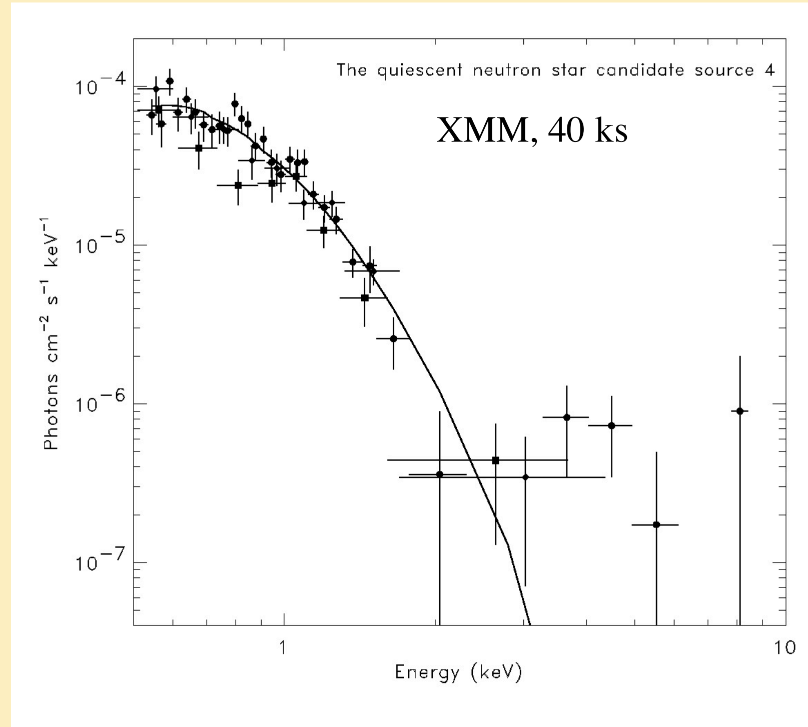
• Metals continuously supplied by accretion, but expect primarily pure hydrogen atmosphere due to rapid gravitational settling. Simple atmosphere modeling!



NGC 5139 (ω Cen)



Rutledge et al. (2002)



Gendre et al. (2003)

R_∞ (d/5 kpc)	$kT_{eff,\infty}$	N_H (10^{20} cm^{-2})
13.6 ± 2.1 km	67^{+2}_{-2} eV	9 ± 2.5

NS Radii from Quiescent LMXBs

Name	R_∞ (km/D)	D (kpc)	$kT_{eff,\infty}$ (eV)	N_H (10^{20} cm^{-2})	Ref.
omega Cen (Chandra)	13.5 ± 2.1	5.36 ±6%	66^{+4}_{-5}	(9)	Rutledge et al (2002)
omega Cen (XMM)	13.6 ± 0.3	5.36 ±6%	67 ±2	9 ± 2.5	Gendre et al (2003)
M13 (XMM)	12.6 ± 0.4	7.80 ±2%	76 ±3	(1.1)	Gendre et al (2003)
47 Tuc X7 (Chandra)	34_{-128}^{+22}	5.13 ±4%	84^{+13}_{-12}	$0.13^{+0.06}_{-0.04}$	Heinke et al (2003)
M28 (Chandra)	$14.5_{-3.8}^{+6.9}$	5.5 ±10%	90_{-10}^{+30}	26 ± 4	Becker et al (2003)

Distances: **Carretta et al (2000), Thompson et al (2001)**

Soft X-Ray Transients in Quiescence: Issues

• Sources in globular clusters have well-known distances and N_H

• Field sources with bright (V<17) optical counterparts within ~5 kpc should have distances measurable by *SIM* to ~2%

• Systematic effects: N_H, source variability, power-law component, atmosphere models, metallicity (lines?!)

• Sources in globular cluster *cores* (e.g. 47 Tuc, M28) are crowded, require high angular resolution (~1 arcsec)

NOTE: Same solid angle technique possible in principle using thermal emission from X-ray bursts and current instruments. M-R constraints currently limited by inadequate atmosphere modeling for high T and Comptonization effects: ripe for theoretical study, complicated but tractable. Could also get M from radius-expansion bursts. Could use same sources for bursts and quiescence!

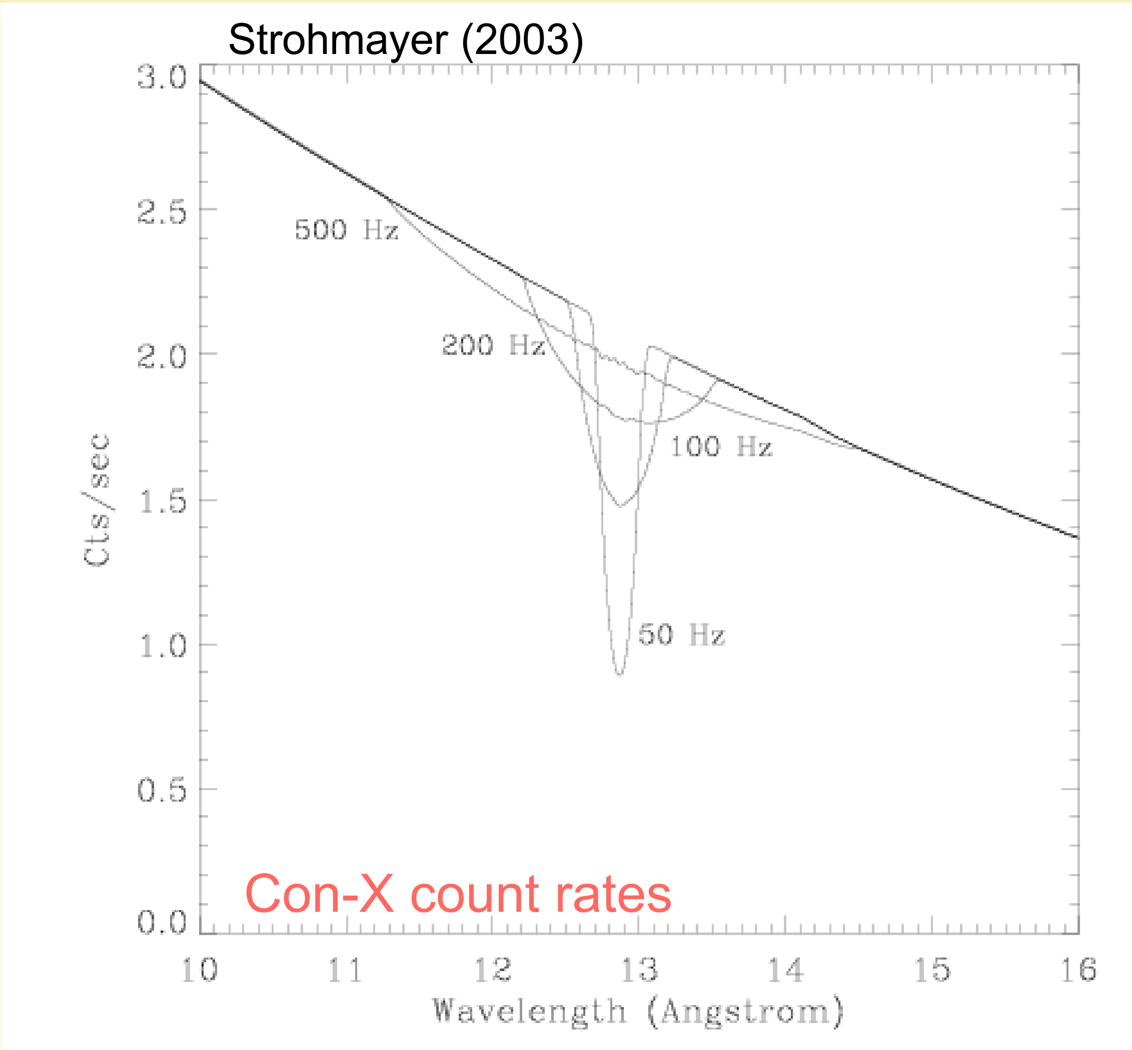
Spectroscopy: Photospheric Lines

- Lines are being found in some neutron stars:
  - EXO 0748-676 (Cottam et al. 2002)
  - 1E 1207.4-5209 (Sanwal et al. 2002)
- Photospheric lines will be subject to gravitational redshift $z(M/R)$
- Pressure (Stark) broadening, depends on M/R^2
- Fine structure, multiplets, magnetic splitting?
- Rotational broadening, ~(Ω R sin i)
- Measurement of line shift and profile, and correct physical interpretation can lead to determination of M and R.

Issues:

- Cyclotron lines: difficult to separate B measurement from redshift
- Cool non-magnetic NSs can have rich atomic line emission, but typically faint when photospheric flux dominates (except during thermonuclear X-ray bursts), heavy elements sink in seconds
- In accreting NSs, metals continuously supplied (even at low Mdot)
- Rotational broadening very serious for >100 Hz

Effect of Rotational Broadening on Narrow Lines

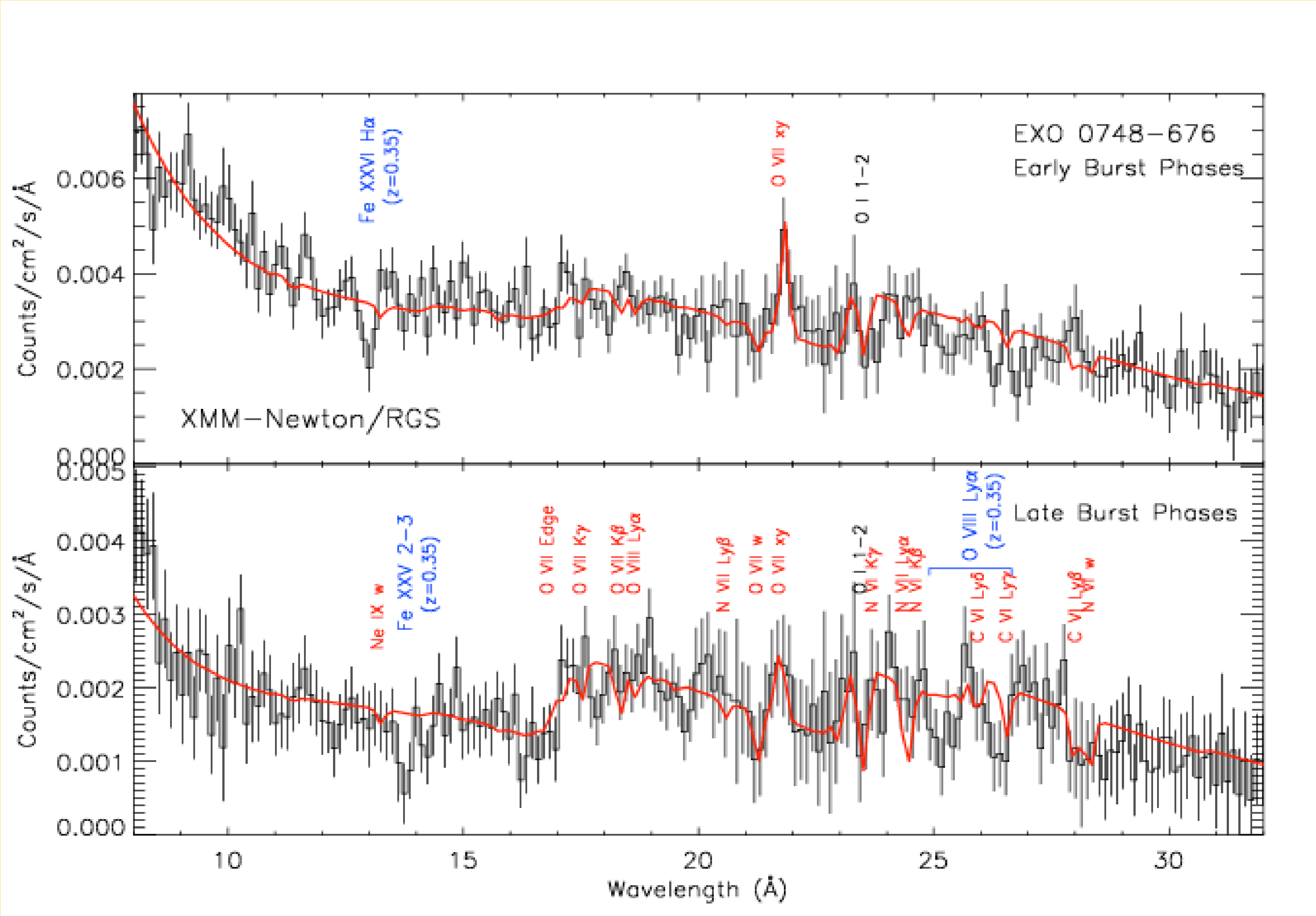


- Lines features from NS surface will be broadened by rotational velocities.
- For many sources, the rotational broadening will dominate (for example, Stark broadening).
- For known spins, velocity gives radius information.
- Asymmetric and double-peaked shapes possible, can constrain emitting surface.

Ozel, Psaltis, Datta, Kapoor, Bildsten, Chang, Paerels.

Photospheric Lines from Thermonuclear Bursts? EXO 0748-676

Cottam, Paerels, & Mendez 2002, Nature



Gravitational Redshift Measurement During Type I Bursts

•Cottam, Paerels and Mendez 2002 (Nature, 420, 51) reported the detection of the n=2-->3 transition of iron during Type I bursts. Data from XMM/Newton of 28 bursts (3.2 ksec) from EXO 0748-676 were co-added to make two separate spectra:

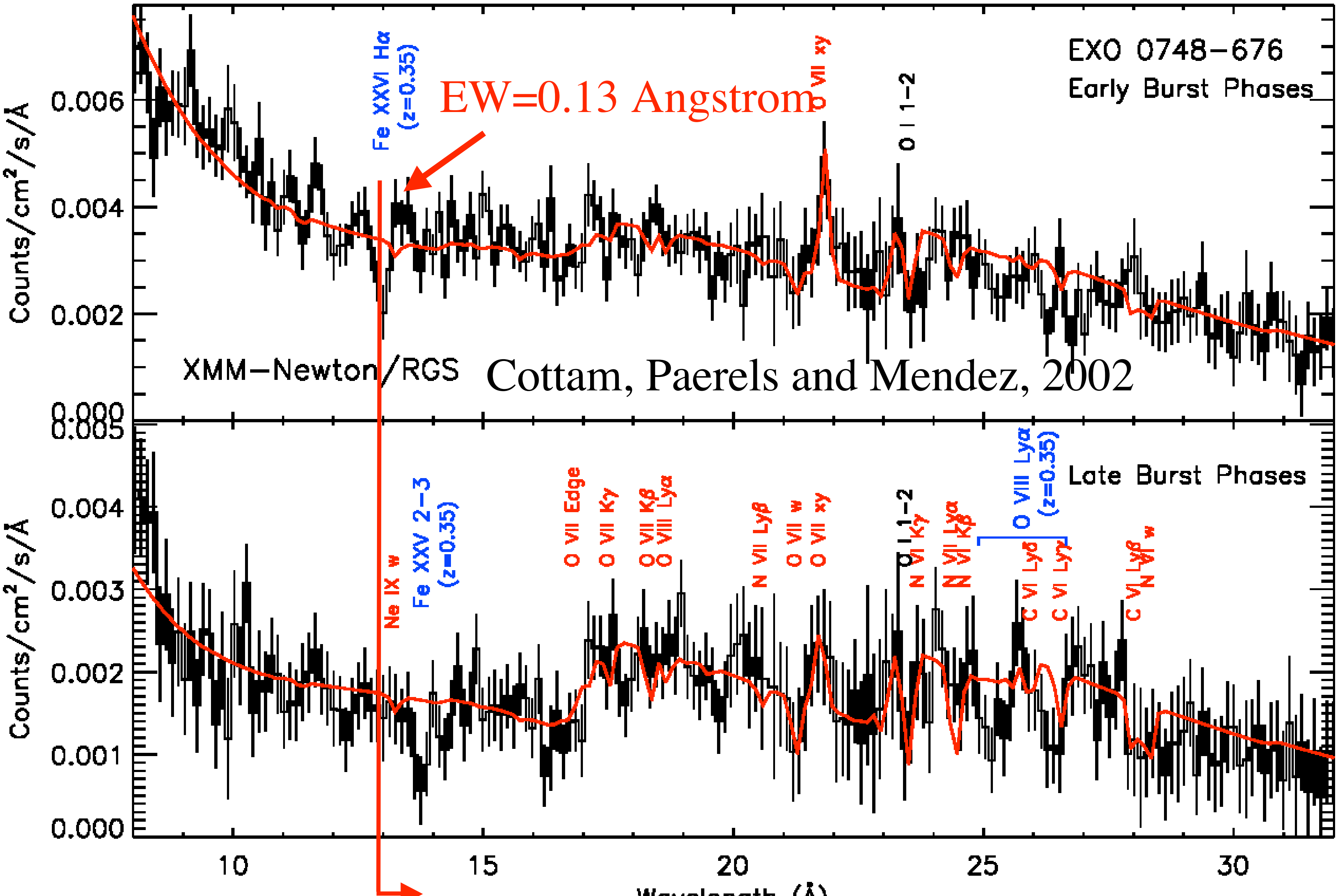
$\boxed{z=0.35}$

1. Bright phase, surface temperature T_{eff}>1.8 keV
   n=2-->3 (Balmer line) seen from hydrogenic iron
2. Dimmer phase, surface temperature less than 1.5 keV
   n=2-->3 of helium-like iron.

• In terms of the atomic physics and temperatures, iron is just about the only nucleus present which can have a bound electron, as $E_{\rm bind} = -9.2\ {\rm keV}(Z/26)^2$ and a naïve application of the Saha equation yields:

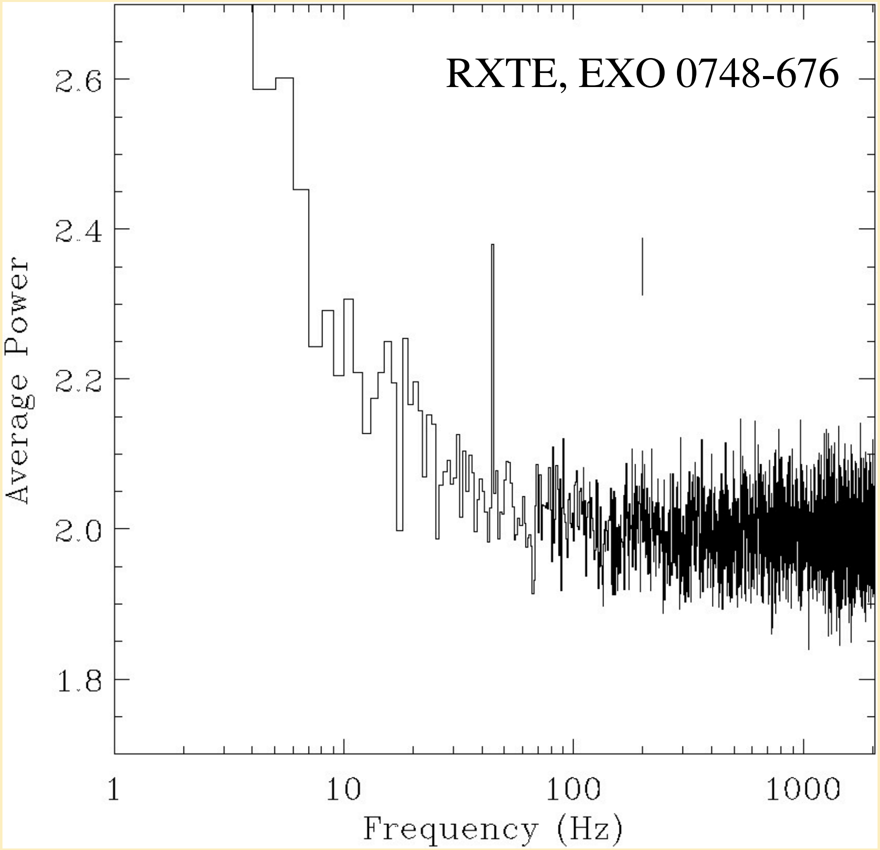
$$kT_{1/2} \approx -\frac{E_{\rm bind}}{\log(n_Q/n_e)} \approx 1.3\ {\rm keV}$$

(slide from Lars Bildsten)



Line energy shifts due to H-like becoming He like as atmosphere cools

Rotation Rate of EXO 0748-676



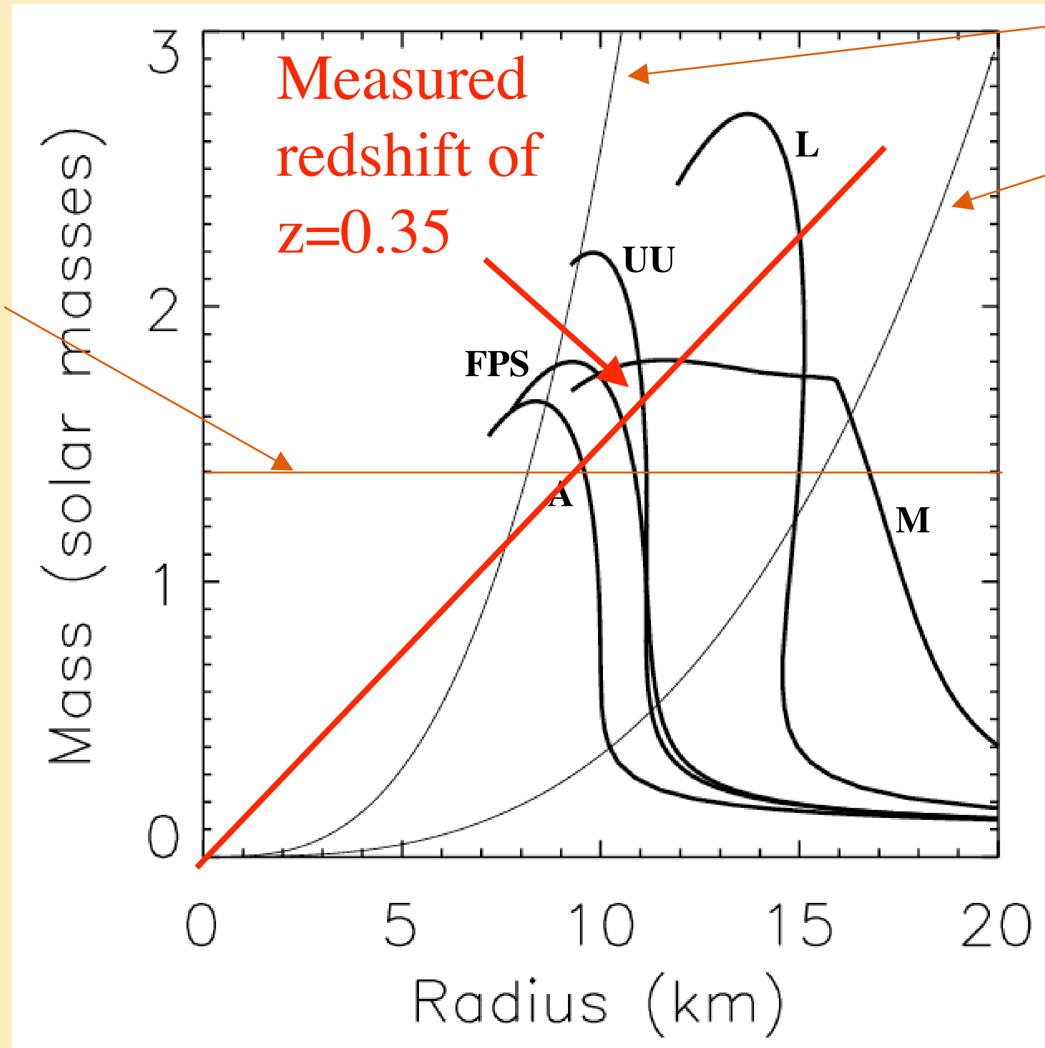
Villarreal & Strohmayer (2004)

One would not expect to see such a narrow photospheric absorption line from a NS spinning at a few hundred Hz (as widely expected for most X-ray bursters)

This is *especially* true for EXO 0748-676, which is an X-ray dipper and thus must have sin $i \approx 1$.

However, it turns out that EXO 0748-676 is a SLOW rotator, with f=45 Hz!

Gravitational Redshift and the Mass-Radius Relation



- The mass of this NS is unknown, accretion could easily bring it up to 1.8 solar masses

Issues and Concerns

• Follow-up observations (76 new bursts) of EXO 0748-676 do not detect similar line features. In fact, the entire source spectrum is very different, with a much higher continuum flux. The circumstellar conditions have also changed, as has the accretion rate (which will affect the burst behavior) (Cottam, priv. comm.)

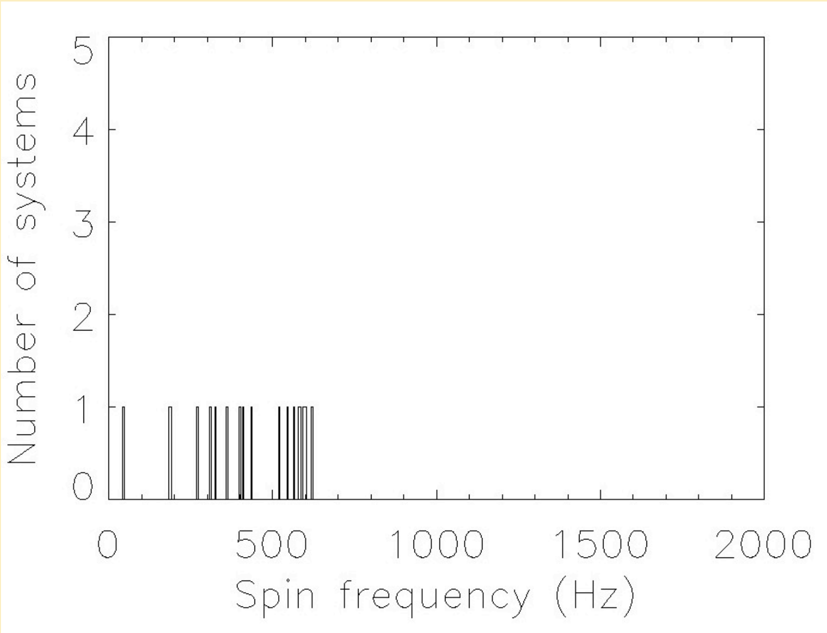
• Lengthy observations of other bursters (e.g., GS 1826-24) have not similar line features. (Rotation?)

• Are the lines real? Reanalysis by team verifies significance of original detection.

• Are the lines photospheric? Plausible story given ionization balance and rotation.

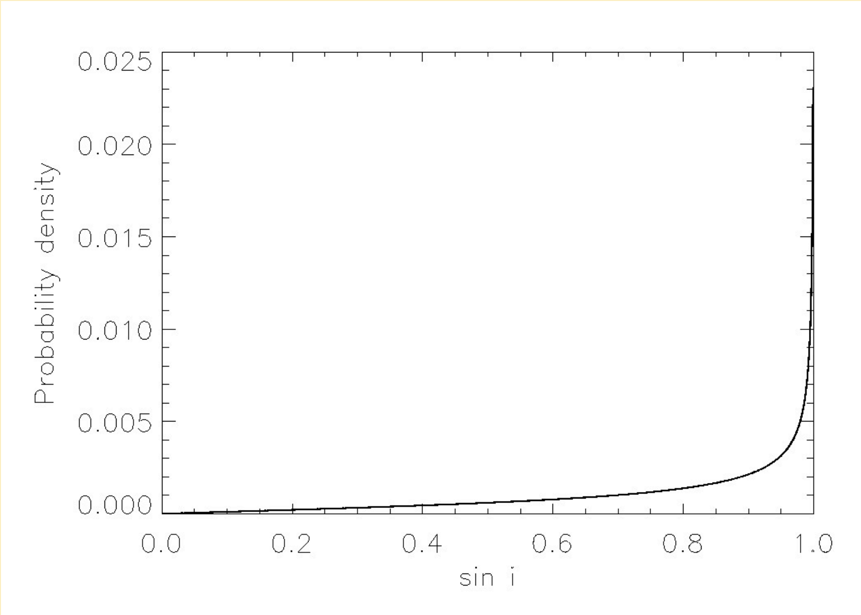
• Line are definitely expected at a level detectable by Con-X/XEUS.

X-Ray Burster Spin Distribution



Chakrabarty (2005)

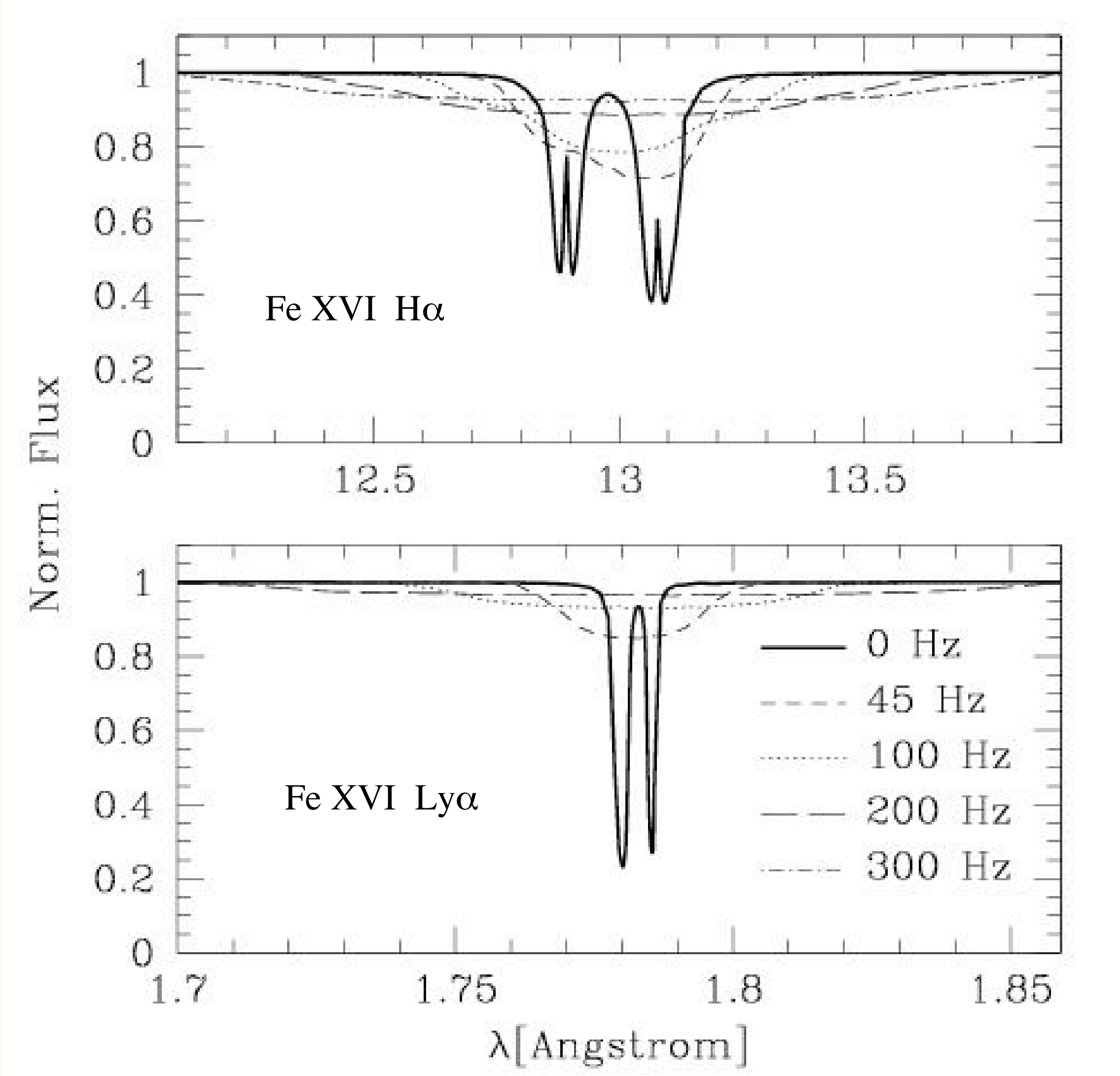
Expected (sin *i*) distribution for random sample



- Most bursters with known spins are rapid rotators. For a random distribution of binary inclinations, the sin *i* factor will not help much to reduce the product ($\Omega\, R \sin i$).

- However, MANY bursters do not have detected spin rates. Signal in EXO 0748-676 was difficult to detect. Are slow rotators common?

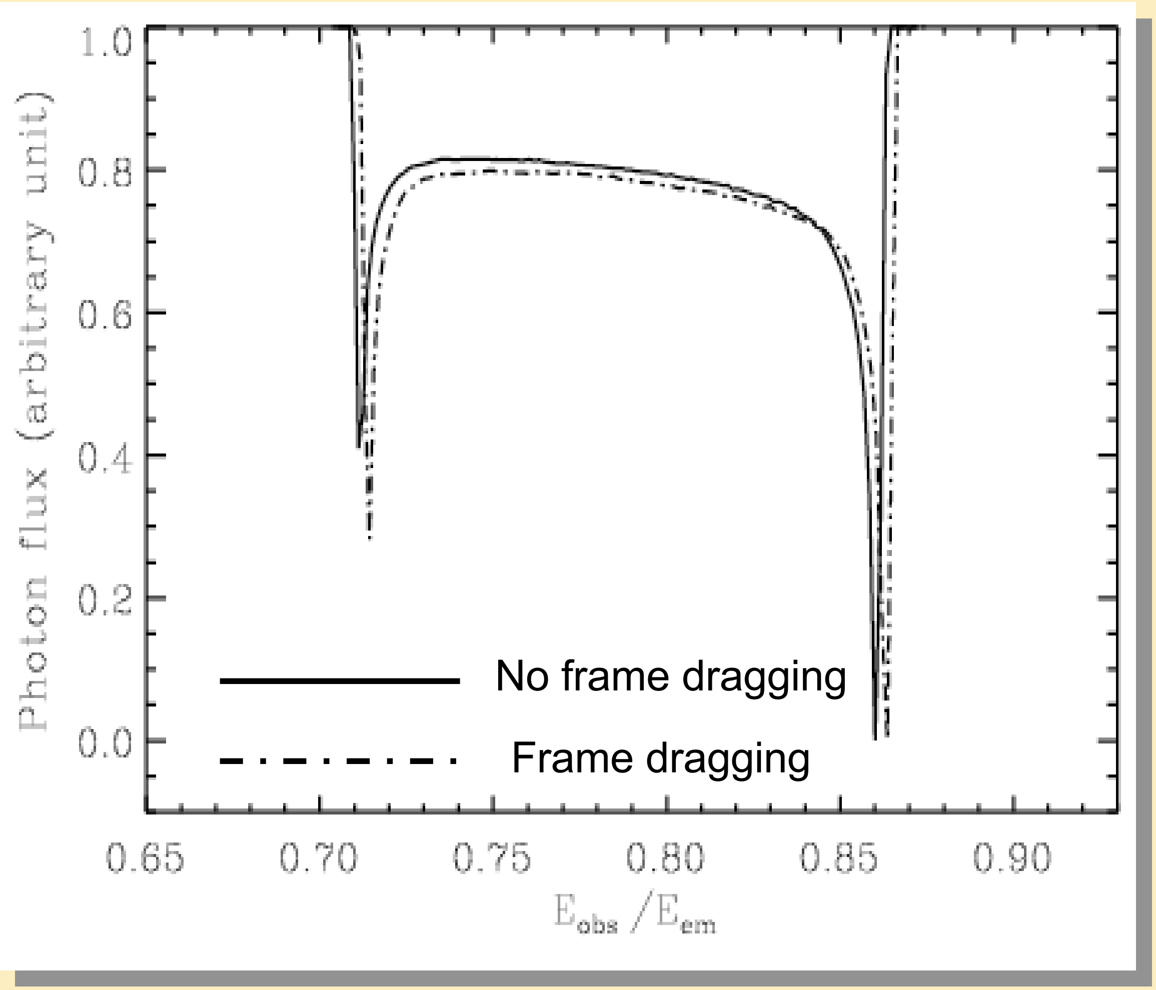
Rotational Broadening of "Structured" Lines



Chang, Bildsten, & Wasserman (2005)

- Even for slow rotators, rotational broadening will be significant if the intrinsic line is not narrow (e.g. fine structure, pressure broadening, magnetic splitting.)
- Burst environment is actually non-LTE problem, appropriate radiative transfer problem must be solved (e.g., Chang et al. 2005)
- Redshift measurements are definitely feasible. Extracting parameters from line profiles MAY be possible, but detailed calculation of line physics required.

Spectral Line Profiles: Probing Frame Dragging Around a Neutron Star

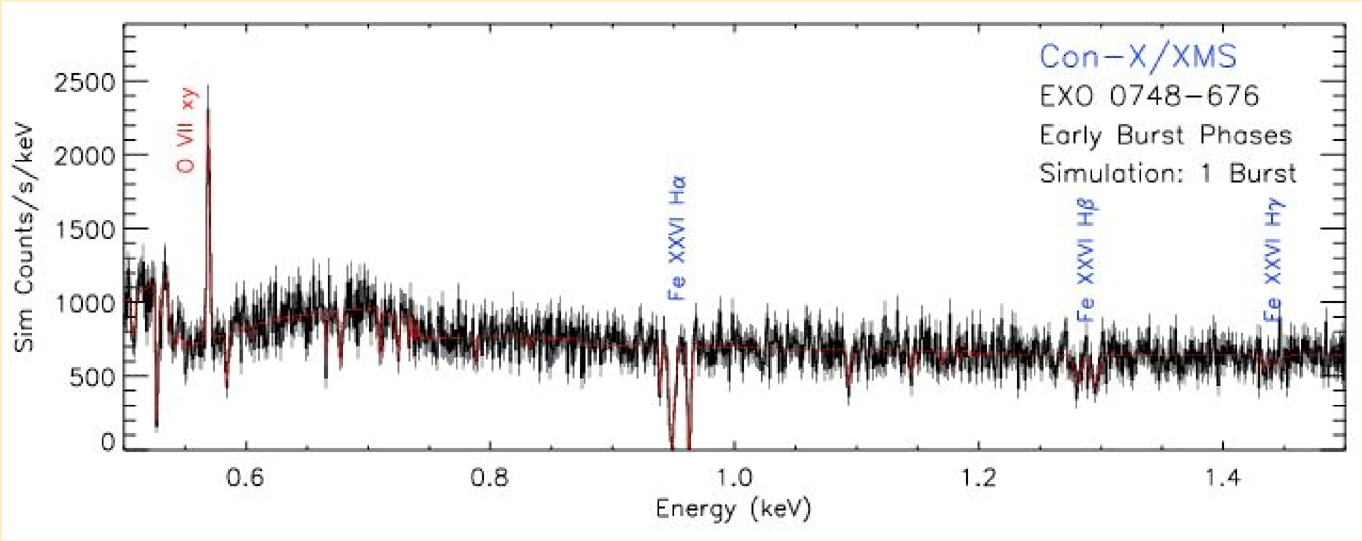


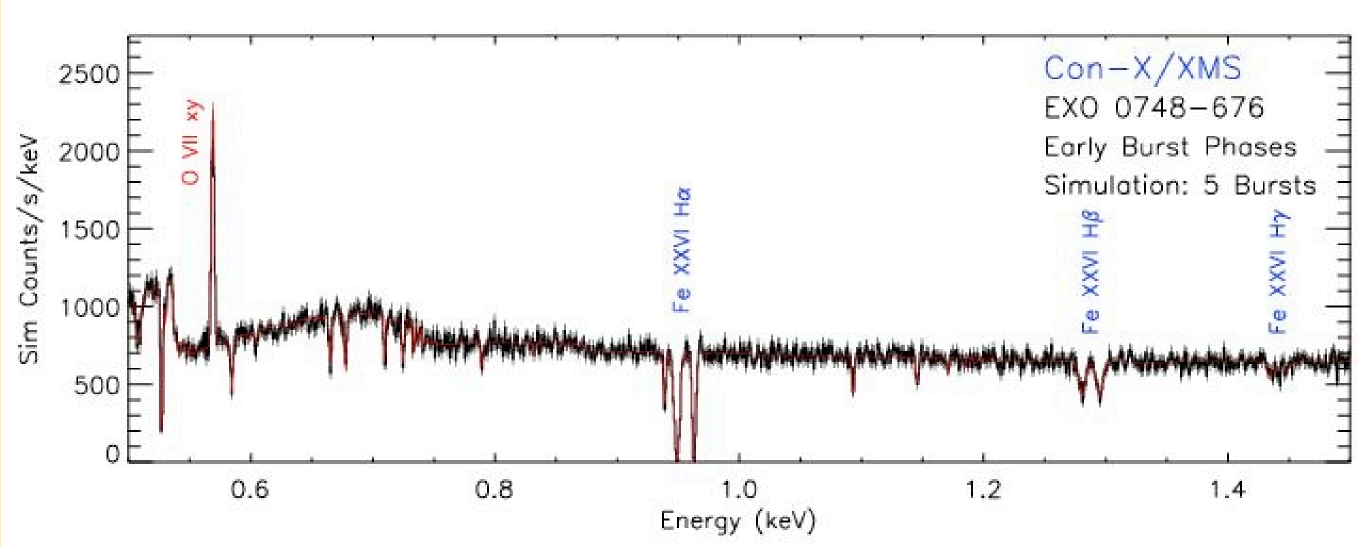
- Accreting neutron stars in binaries spinning at ~300 - 600 Hz.
- v_{rot} ~ 0.1c at surface!
- Linewidth dominated by rotation. Measurement of width can constrain R.
- Double peaked profile when fraction of NS surface emitting (as during burst oscillations).
- Relative depth of two peaks is sensitive to frame dragging term (Bhattacharyya, Miller & Lamb 2003).

NOTE: Assumes intrinsic line is narrow!

Credit: Bhattacharyya, Miller & Lamb (2003)

Simulations: Simple line structure assumed

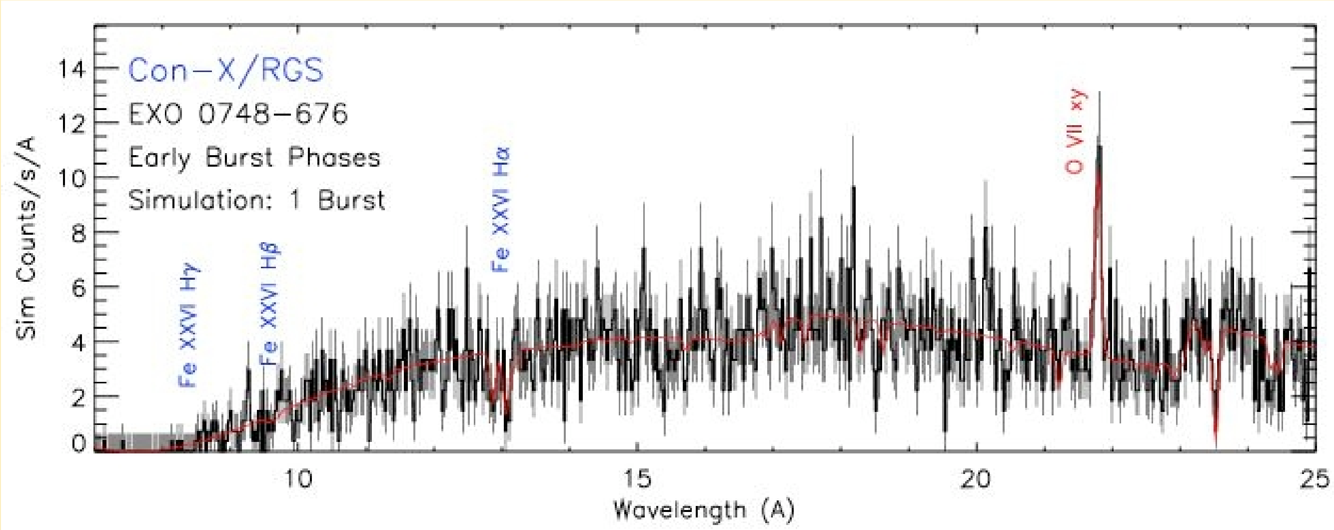


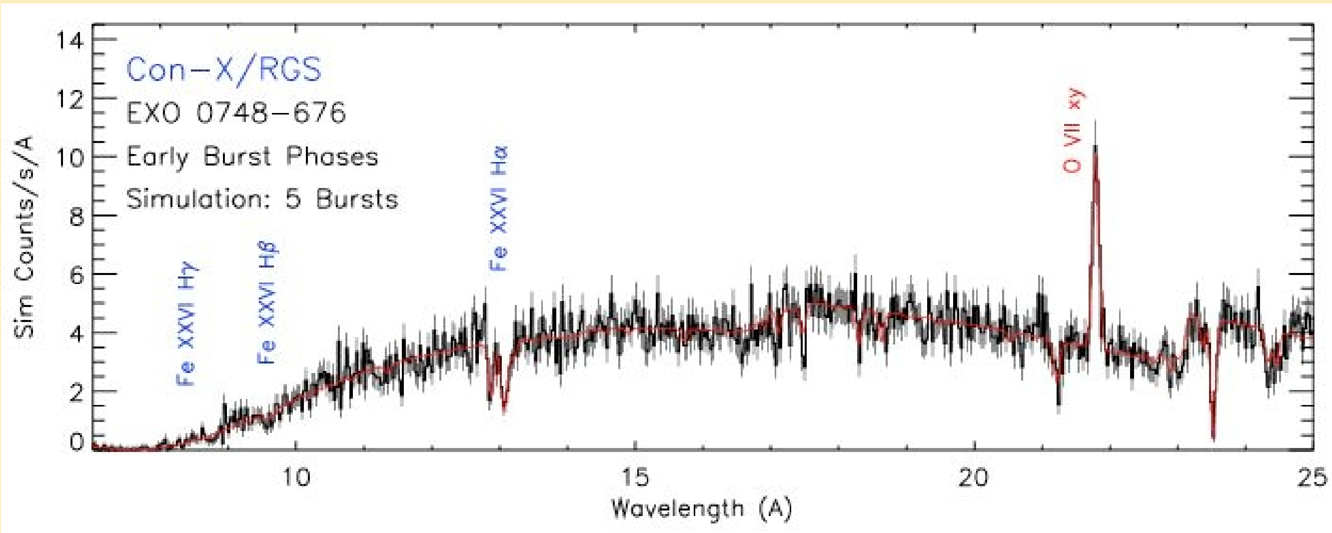


Simulations using Con-X matrix and 3*(ConX) area

(Jean Cottam)

Simulations(2): Simple line structure assumed





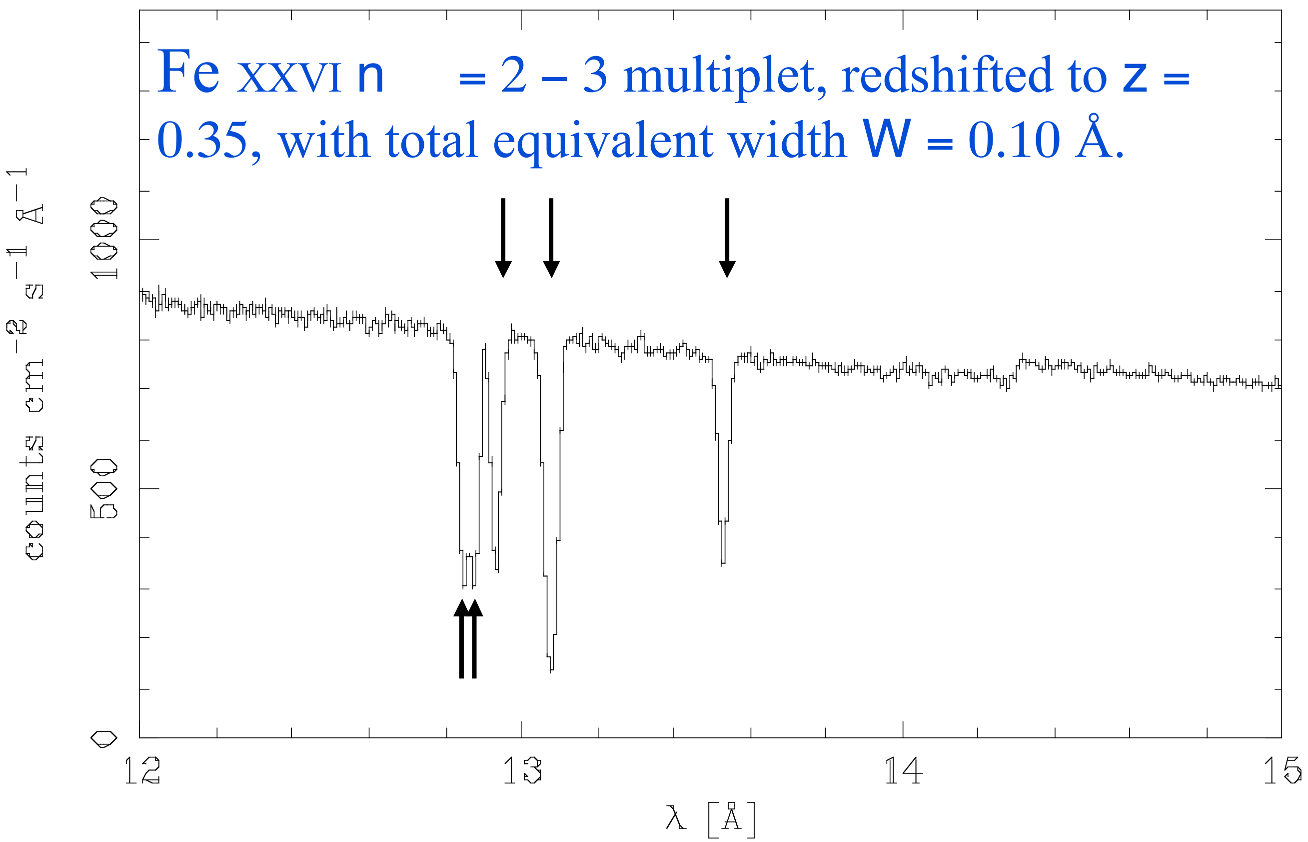
Simulations using Con-X matrix and 3*(ConX) area

(Jean Cottam)

Burst spectra: simulations

(for simulations with complex line structure)

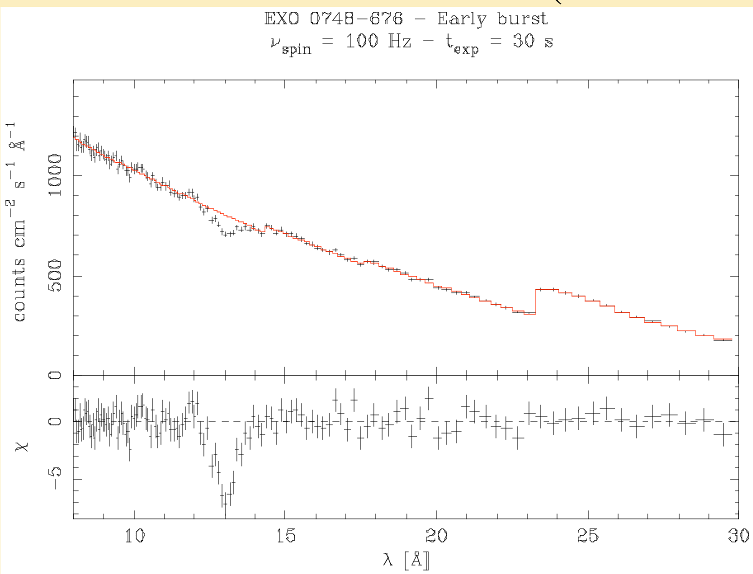
Input Spectrum

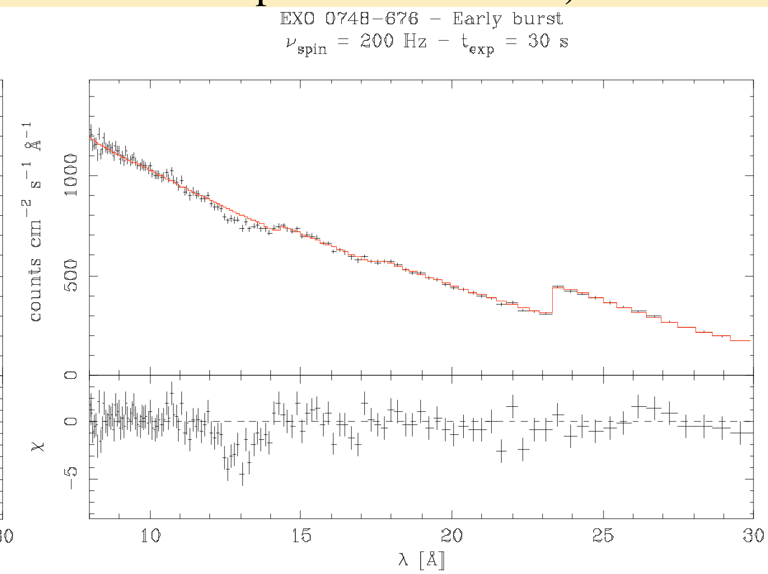


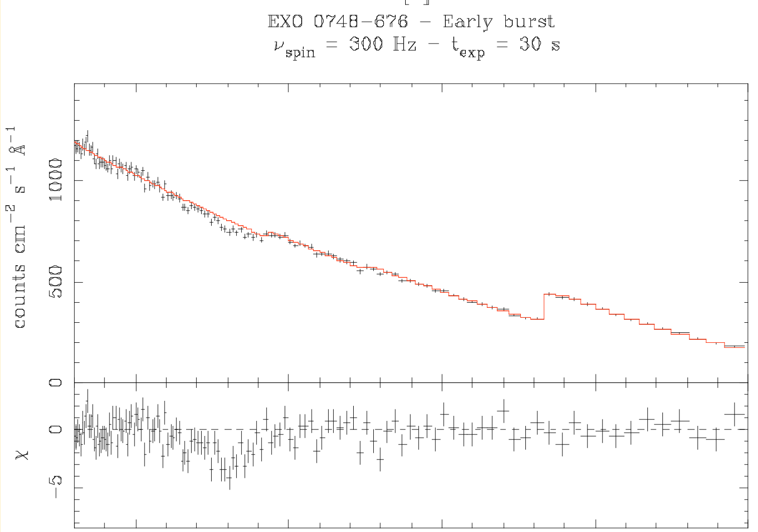
(from Mariano Mendez talk)

Burst spectra: simulations

(for simulations with complex line structure)





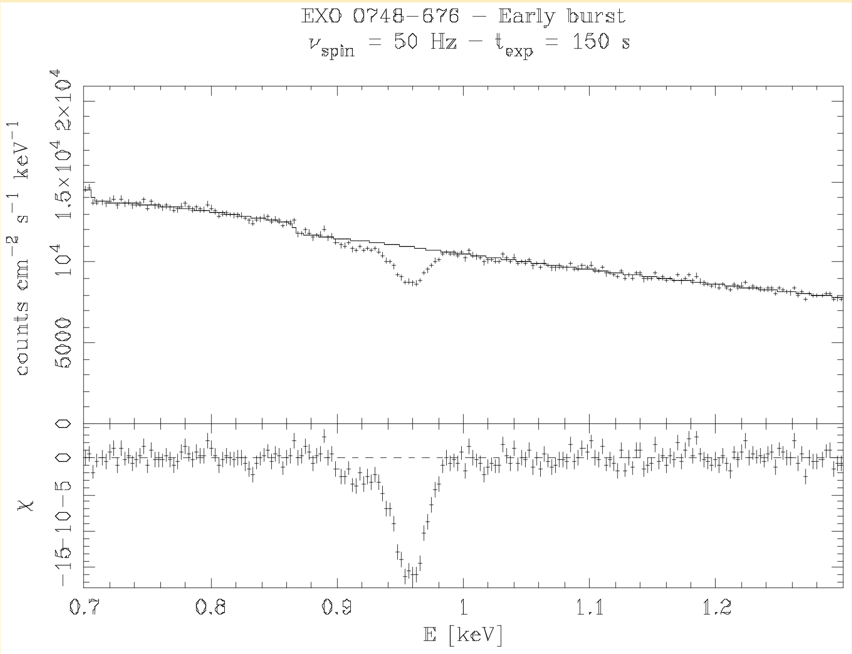


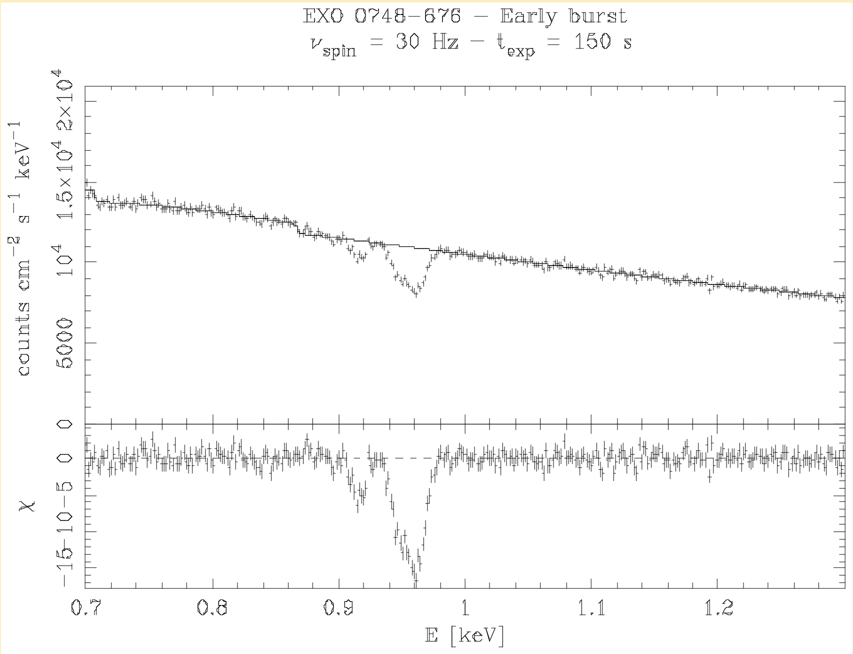
30-second exposures of the early part of a single X-ray burst, for 3 different spin frequencies of the neutron star, and 10-m^2 X-ray detector with a 5-eV spectral resolution.

(from Mariano Mendez talk)

Resolving the multiplet

(for simulations with complex line structure)



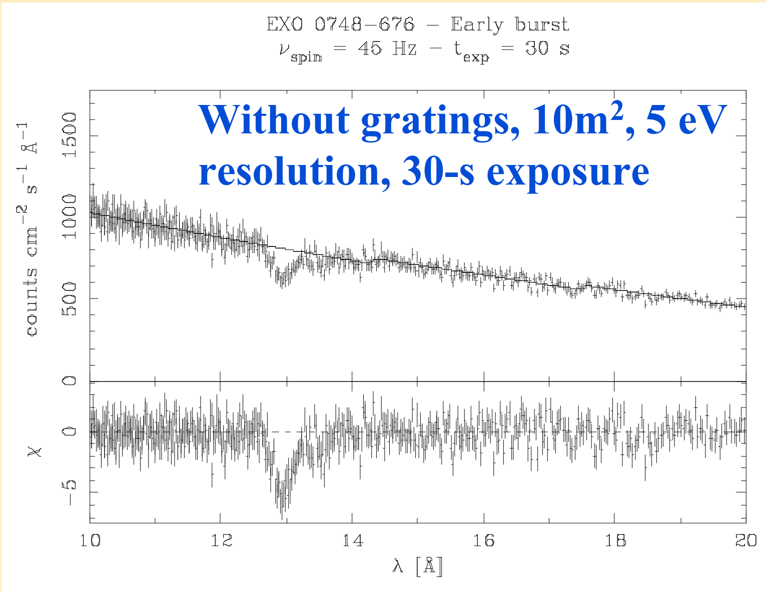


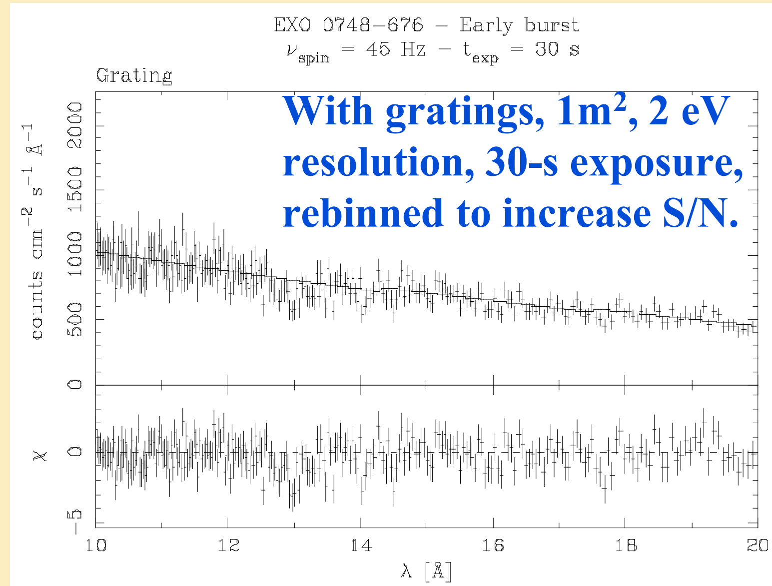
150-second exposures (~5 bursts co-added) of the early part of the bursts, for 2 different spin frequencies of the neutron star (slow rotator). Again, a 10-m^2 X-ray detector with a 5-eV spectral resolution has been used for the simulations.

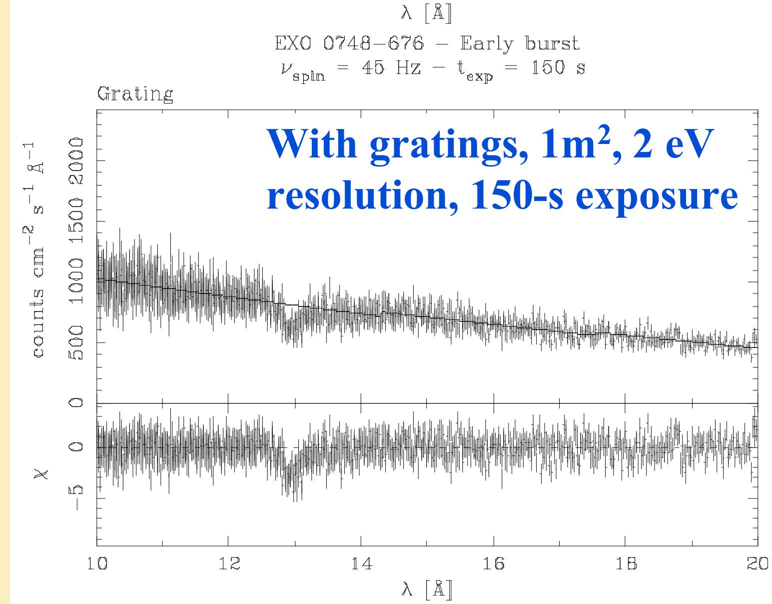
(from Mariano Mendez talk)

Observing with / without gratings

(for simulations with complex line structure)





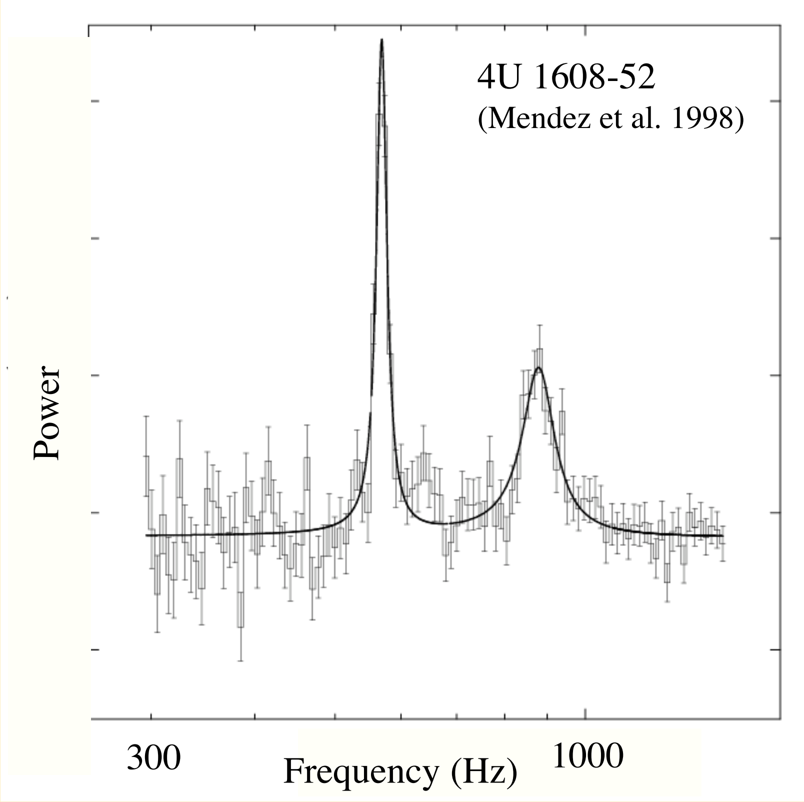


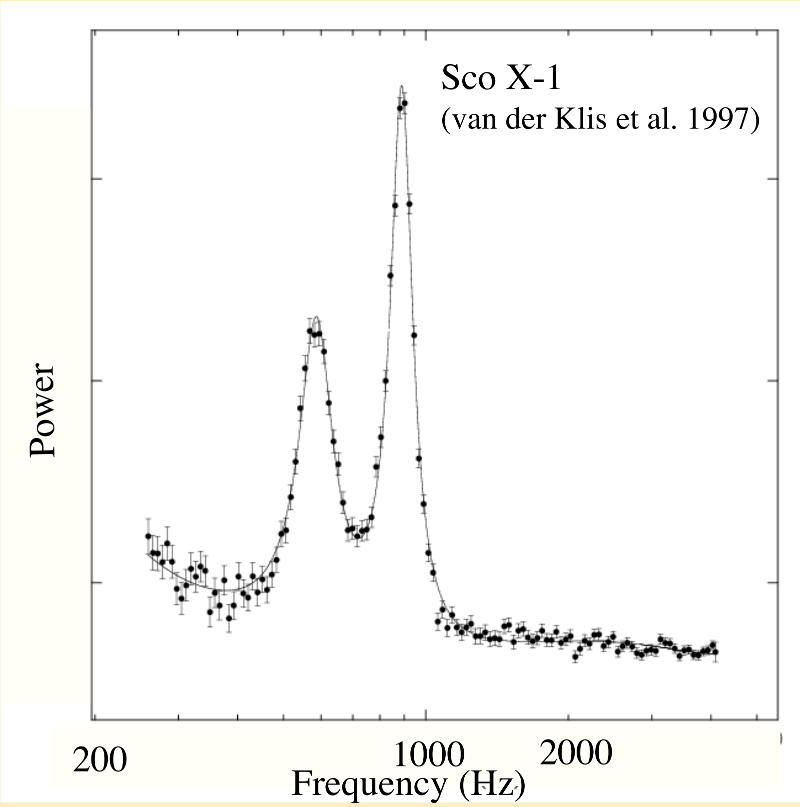
The reduced effective area of the gratings (here assumed to be 10% of the main 10-m² mirror) makes it impossible to detect lines within a single burst. Finer spectral resolution does not provide a gain since lines are intrinsically broad.

(from Mariano Mendez talk)

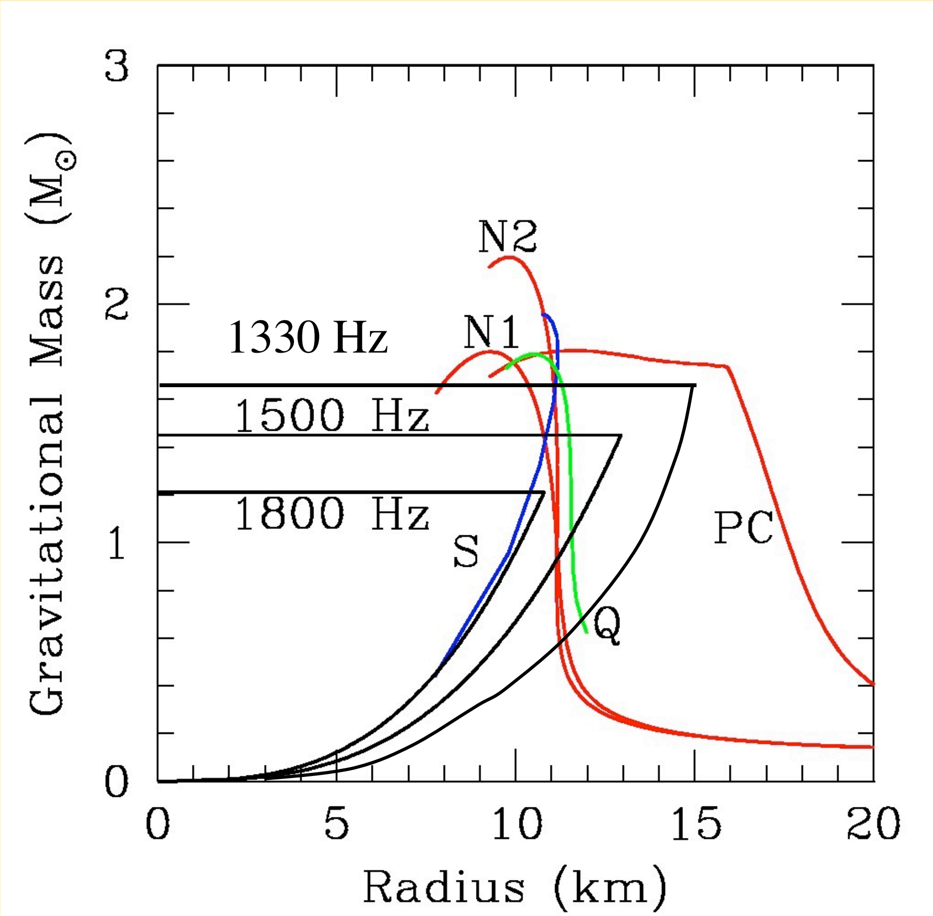
Kilohertz quasi-periodic oscillations (kHz QPOs)

- QPO pairs with roughly constant frequency separation (~300 Hz)
- QPO frequencies drift by hundreds of Hz as X-ray flux changes (200-1200 Hz)
- Particular separation frequency is a characteristic of a given source
- Seen in over 20 LMXBs. Believed to originate in accretion disk.





Neutron Star Oscillations: Getting at Mass and Radius



M. C. Miller (2004)

• Quasi-periodic oscillation pairs (100-1330 Hz) detected in over 20 X-ray binaries.

• Separation frequency set by spin rate. Oscillation frequencies vary with accretion rate, suggesting inner disk orbit origin.

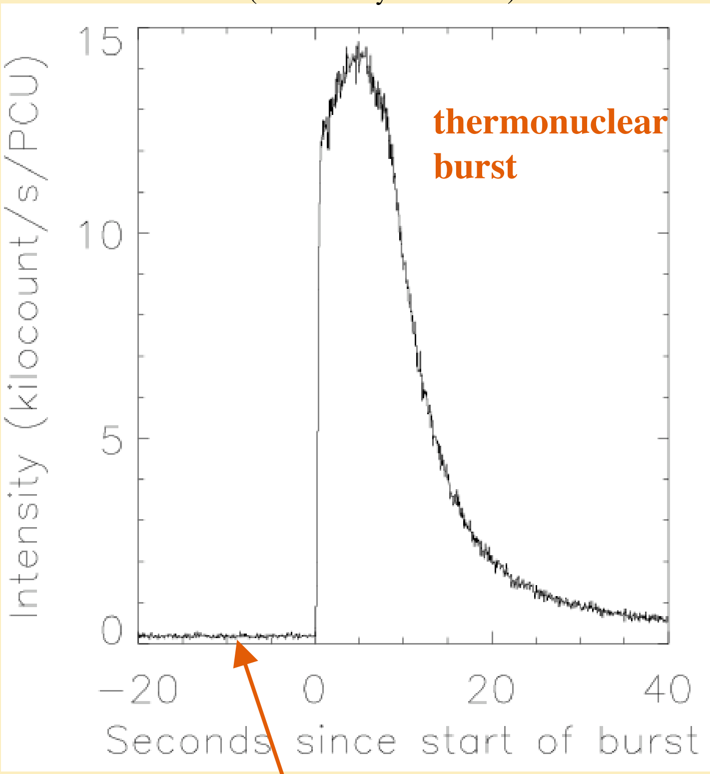
• Oscillation amplitudes decrease as frequencies rise.

• If orbital origin, then geometry of orbits in general relativity constrains allowed mass and radius of neutron star. Fastest oscillation sets strongest constraint. (Current max=1330 Hz)

• Detection at frequencies above 1500 Hz would discriminate between relevant equations of state.

Thermonuclear X-Ray Burst Oscillations

SAX J1808.4-3658 (Chakrabarty et al. 2003)



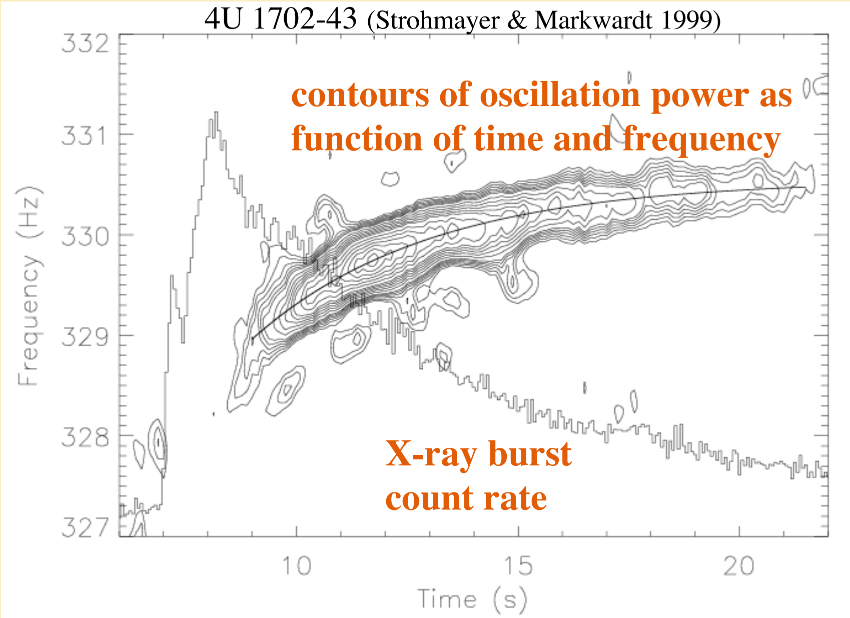
quiescent emission due to accretion

- Nearly coherent msec oscillations during thermonuclear bursts (270-619 Hz). More than 100 examples in over 10 sources, most also with kHz QPOs.

- Frequency drifts by several Hz over a few seconds, reaching an asymptotic maximum characteristic of each source.

- Frequency drift understood as angular momentum conservation in a decoupled burning layer on neutron star surface.

4U 1702-43 (Strohmayer & Markwardt 1999)



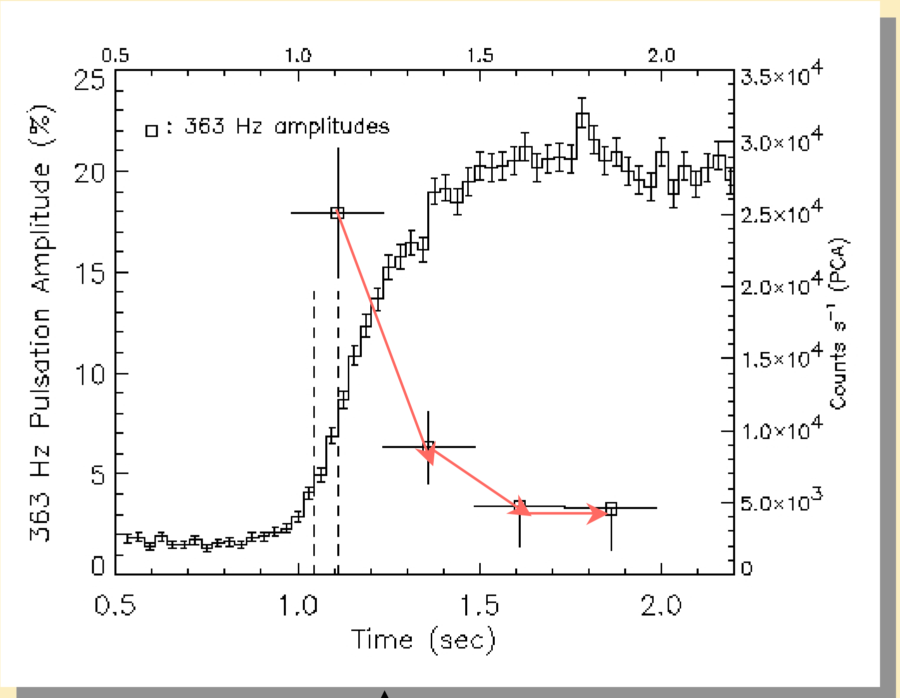
- Amplitude evolution in burst rise interpreted as spreading hot spot on rotating NS surface.

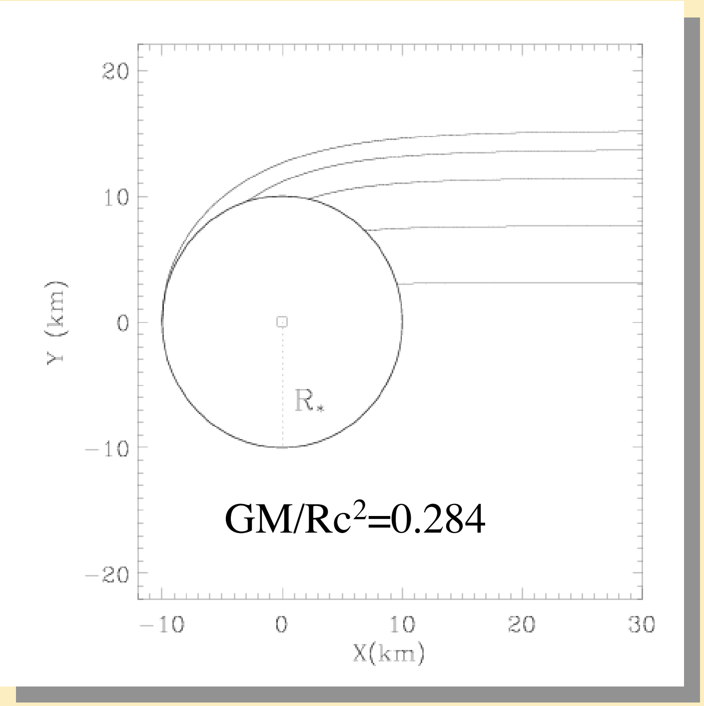
- Oscillations in burst tail not yet understood.

- “Nuclear-powered” pulsars!

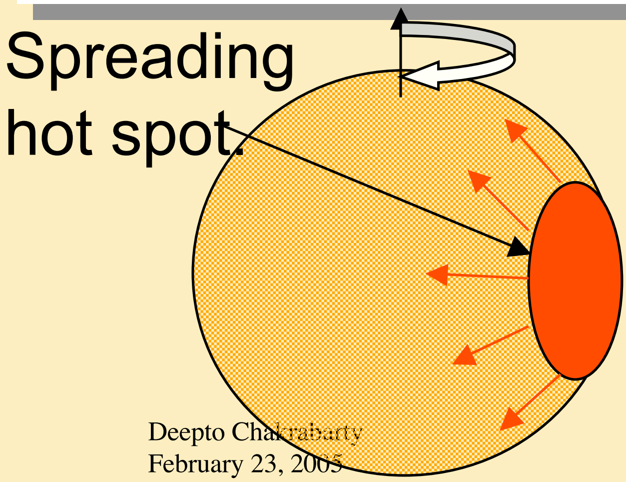
Timing and Spectral Evidence for Rotational Modulation

Strohmayer et al. (1997)





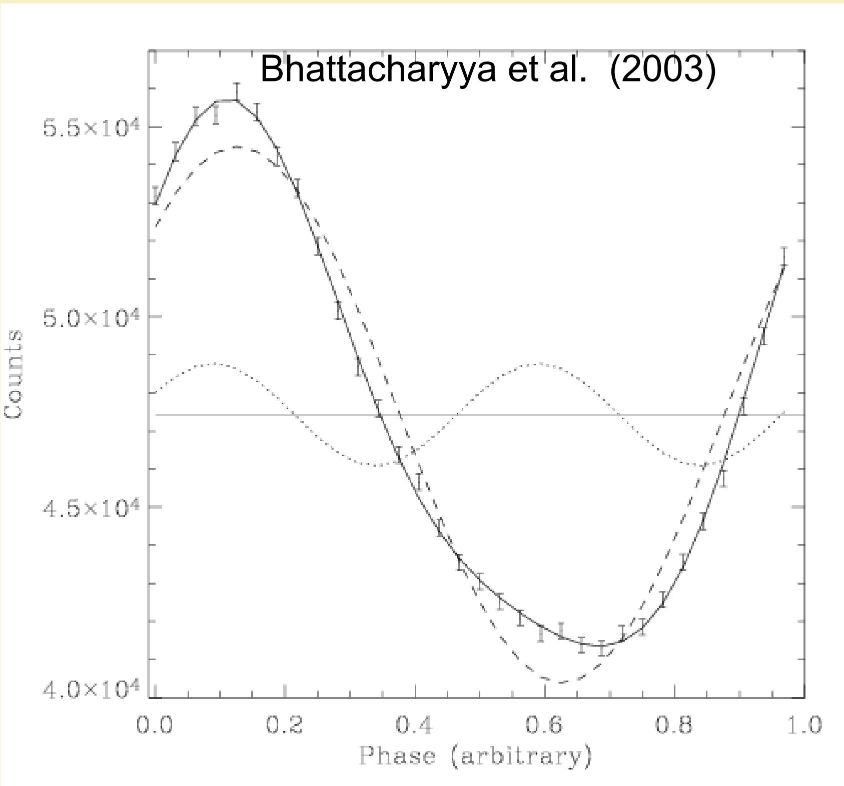
Strohmayer (2004)



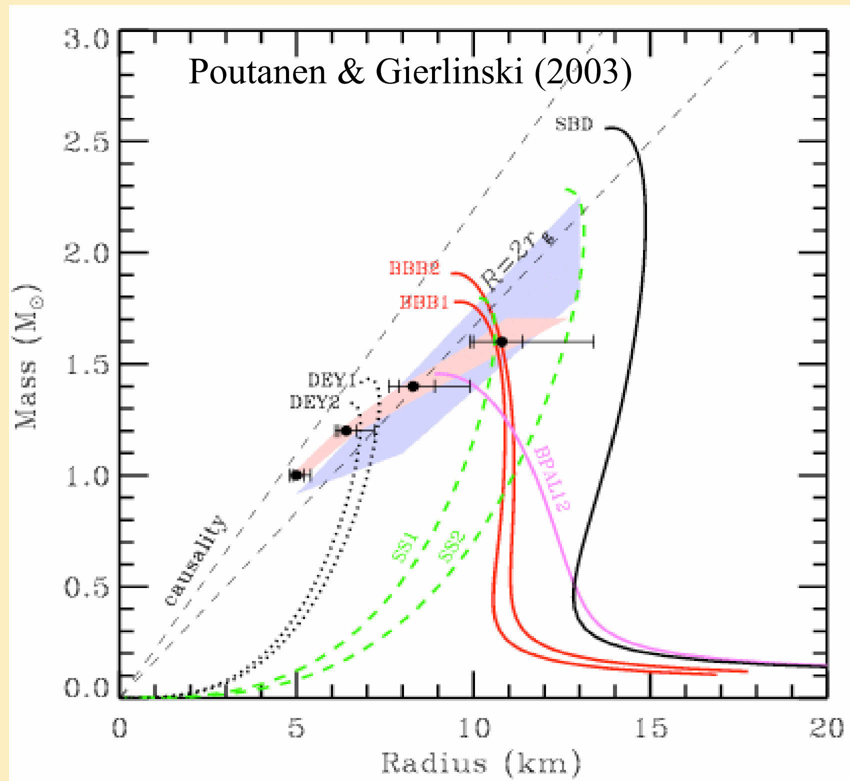
- Oscillations caused by hot spot on rotating neutron star
- Modulation amplitude drops as spot grows.
- Spectra track increasing size of X-ray emitting area on star.

(slide from Tod Strohmayer)

Mass–Radius Constraints: Recent Timing Results

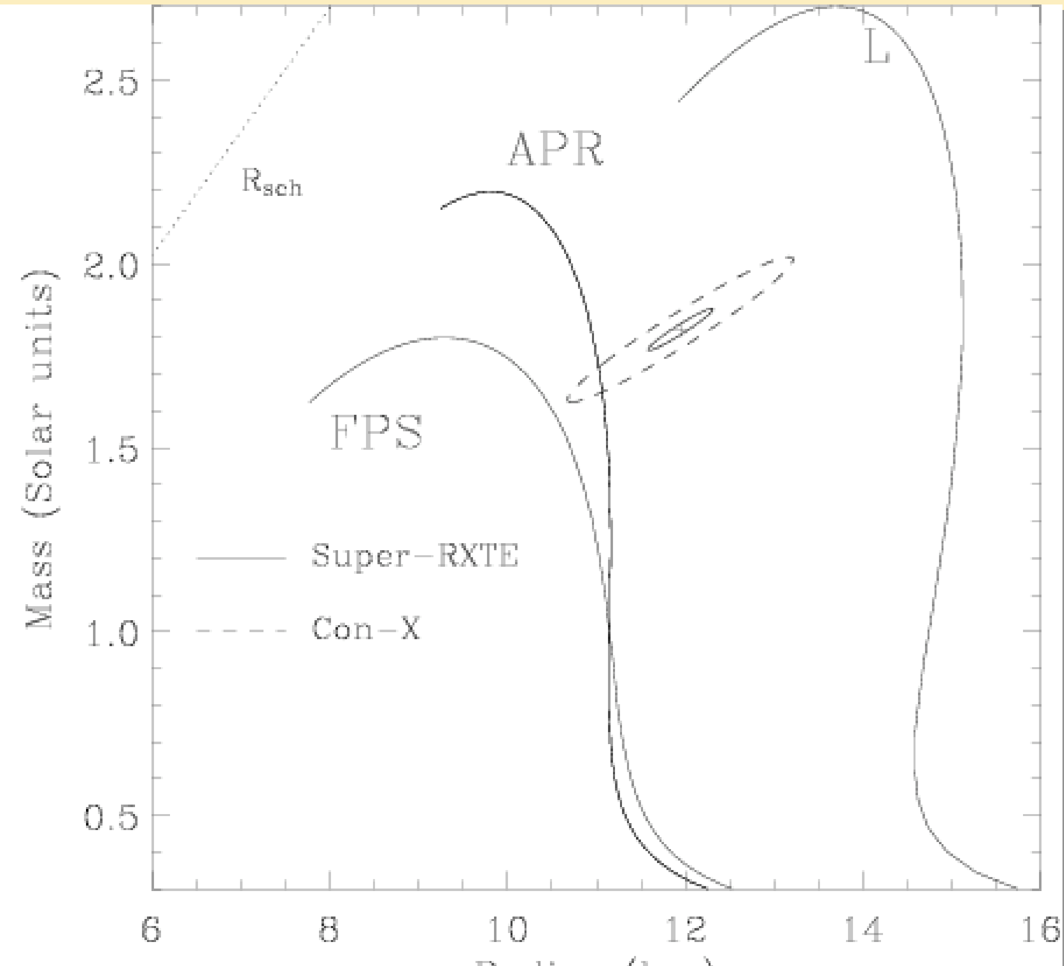


- Comparison of constraints from SAX J1808.4-3658 (Poutanen & Gierlinski 2003, red), and XTE J1814-338 (Bhattacharyya et al. 2004, blue).
- Encouraging overlap of allowed regions



- 27 X-ray bursts from XTE J1814-338 (ms pulsar).
- High signal to noise burst oscillation profiles, with first ever harmonics.

Burst Oscillations and M - R Constraints for Neutron Stars

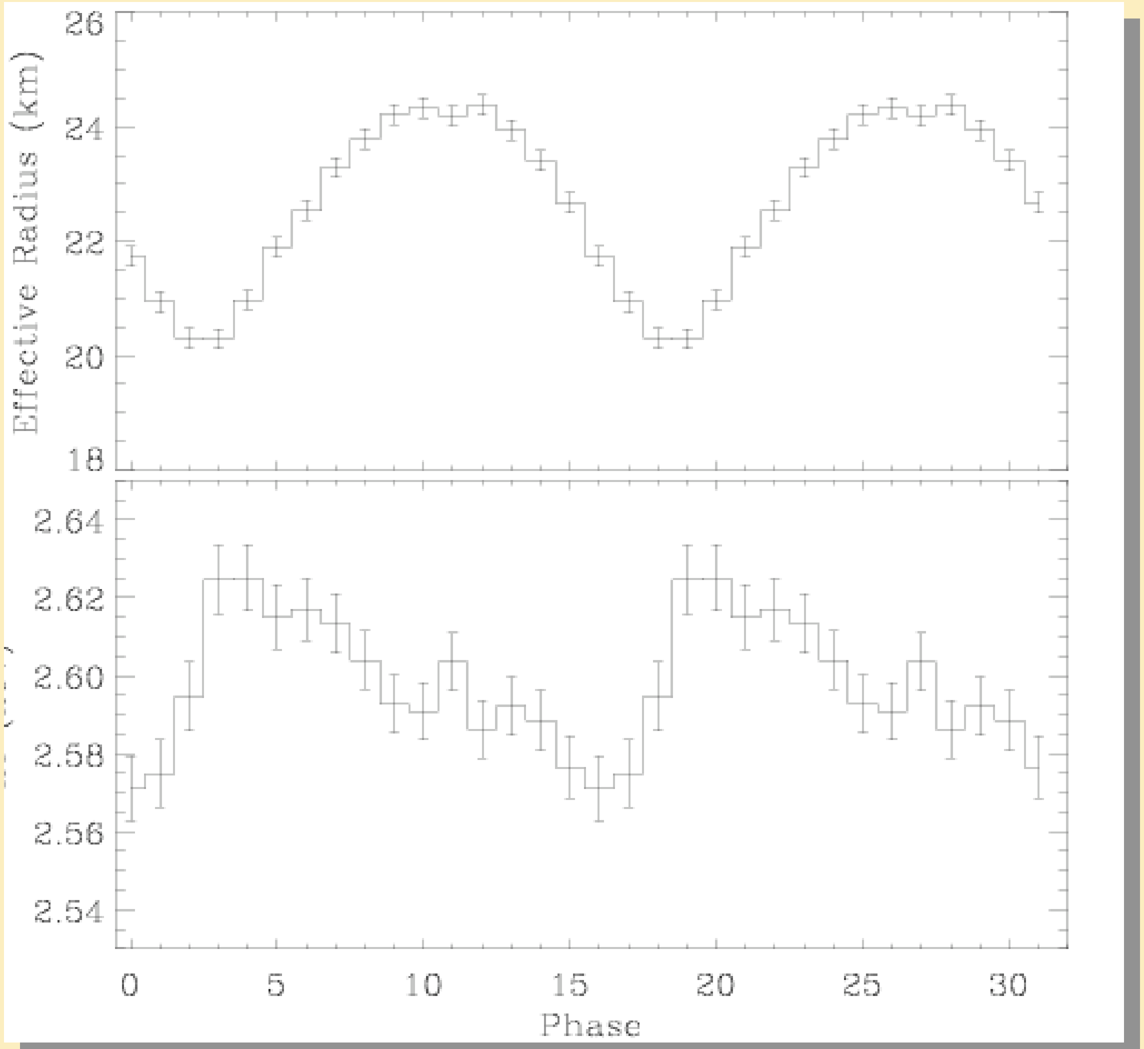


Strohmayer (2003)

- Pulse shapes of burst oscillations encode information on the neutron star mass and radius.
- Modulation amplitude sensitive to compactness, M/R.
- Pulse sharpness (harmonic content) sensitive to surface velocity, and hence radius for known spin frequency.
- Geometry and evolution of the hot region can be a complicating factor.
- Statistical limits for future missions look promising.

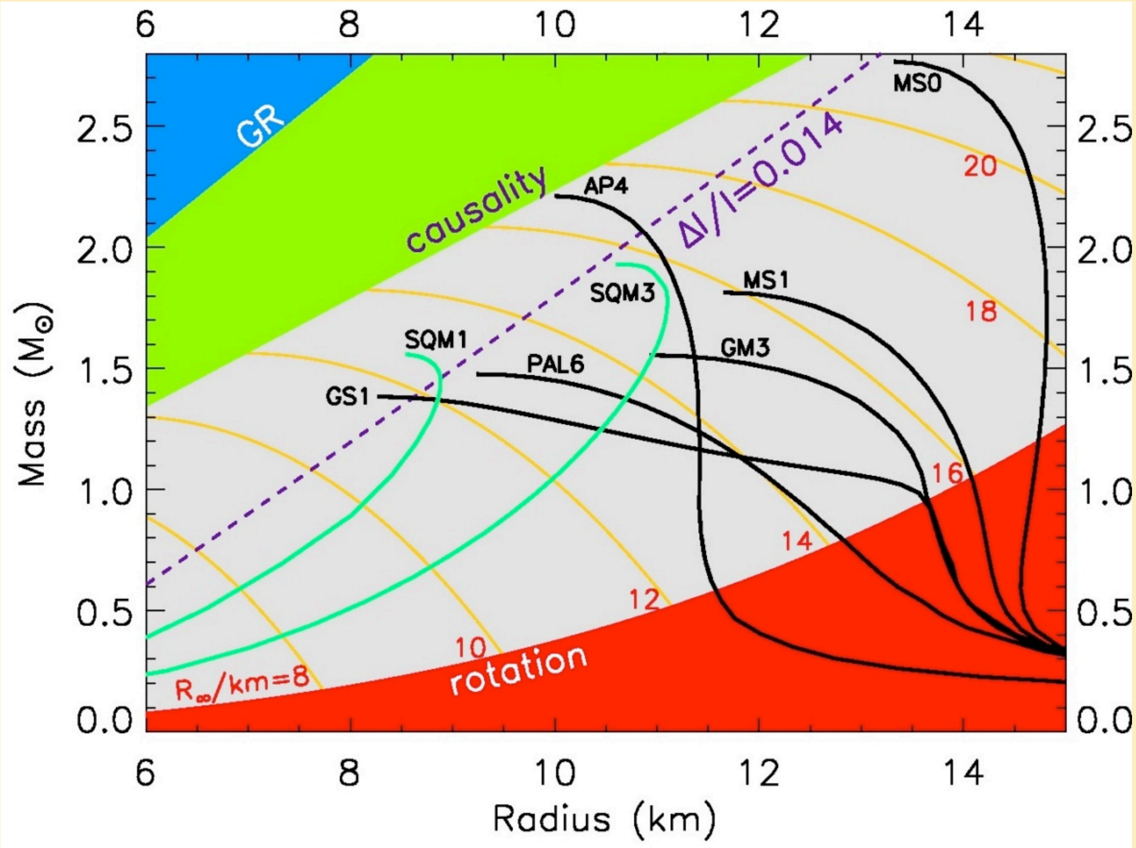
(slide from Tod Strohmayer)

Pulse Phase Spectroscopy: Seeing the Surface Velocity



- Simulation for J1814-like burst, with 10x RXTE/PCA.
- The rotational doppler shift can be seen in the phase dependence of the fitted kT.
- Could provide a measurement of radius.

(slide from Tod Strohmayer)



Lattimer & Prakash (2004)

Using existing data, constraints using the various techniques already identify a consistent allowed region on the *M-R* diagram.

With Con-X/XEUS, it should be possible to actually associate a particular point on this diagram for each object studied, allowing us to map out the allowed *M-R* curve.

XEUS/Con-X will do well in all of the techniques described, although the required capabilities are rather different for the spectroscopic and timing approaches.

See charts from Mendez:

Critical capabilities: 1. Spectroscopy

- Angular resolution: Not a driver
  ~10 arcsec to avoid confusion.
- Field of view: Not a driver
  Point-like sources.
- Band pass: ~0.3 keV – 12 keV (~1 Å – 30 Å)
  Lower bound to detect high-order Paschen lines.
  Upper bound to constrain continuum around Fe Lyα.
- Spectral resolution: ~3 eV at 1 keV
  For typical rotational/pressure broadening.
- Effective area: As large as possible.
  At least 10 m^2 for single-burst line detection (for slow/moderate rotators).
- Max. count rate: ~10^5 counts/s during 1–5 s (burst peak).
  Pile-up may be a problem. Defocusing?
- Time resolution: Not a driver.

Critical capabilities: 2. Timing

- Angular resolution: Not a driver
  ~10 arcsec to avoid confusion.
- Field of view: Not a driver
  Point-like sources.
- Band pass: ~1 keV – 25 keV (~ 0.5 Å – 12 Å)
  Amplitude of variability increases with energy.
- Spectral resolution: Not a driver
  Some spectral information, ΔE/E _ 10%, desirable.
- Effective area: As large as possible.
  See talk by Didier Barret.
- Max. count rate: ~5 x 10^6 counts/s (see Didier Barret's talk).
  Pile-up may be a problem. Defocusing?
- Time resolution: $\tau \sim 10\ \mu$s or less.